

## LA-UR-21-23359

Approved for public release; distribution is unlimited.

Title: Detector Fundamentals for Reachback Analysts

Author(s): Karpus, Peter Joseph  
Myers, Steven Charles

Intended for: 2021 Spectroscopic Alarm Adjudication Course

Issued: 2021-04-08

---

**Disclaimer:**

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by Triad National Security, LLC for the National Nuclear Security Administration of U.S. Department of Energy under contract 89233218CNA000001. By approving this article, the publisher recognizes that the U.S. Government retains nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.



# **Detector Fundamentals for Reachback Analysts**

**Pete Karpus & Steve Myers (emeritus)**

LA-UR-21-XXXXX

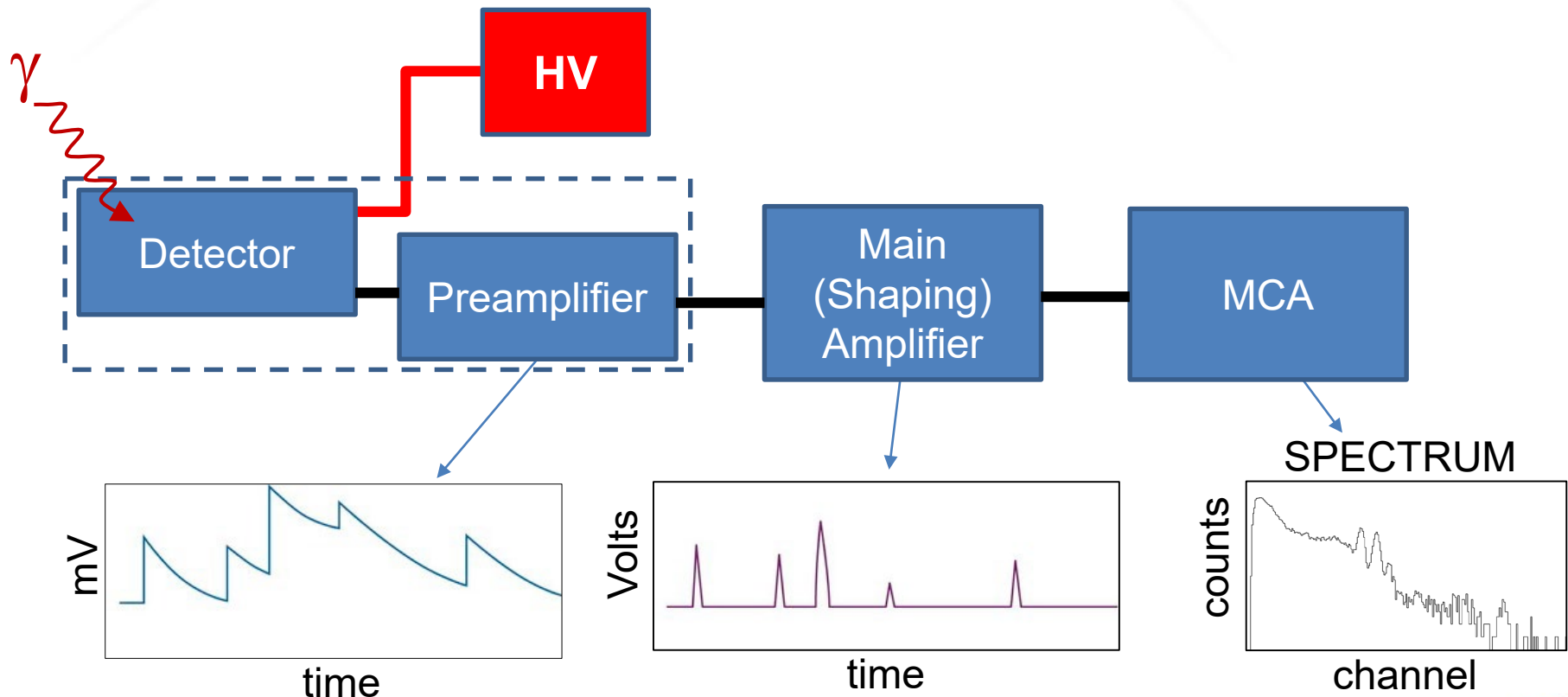
# Introduction

- This presentation provides an overview of common detector concepts
  - Gamma-Ray Detector system components
  - Intrinsic and absolute efficiency
  - Resolution and linearity
  - Operational issues and limits
  - Neutron Detection
  - Basic Statistical Concepts



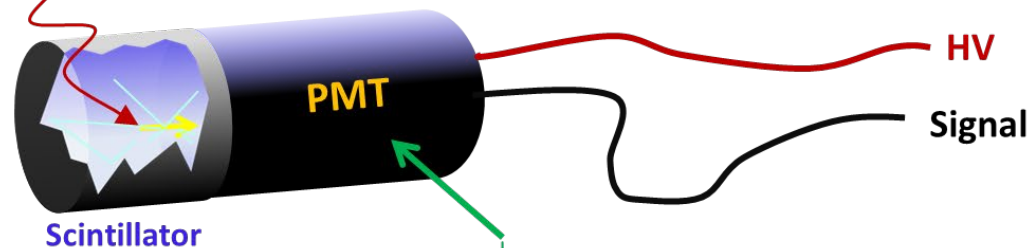
# Detector System and Components

# Typical Analog Detector System

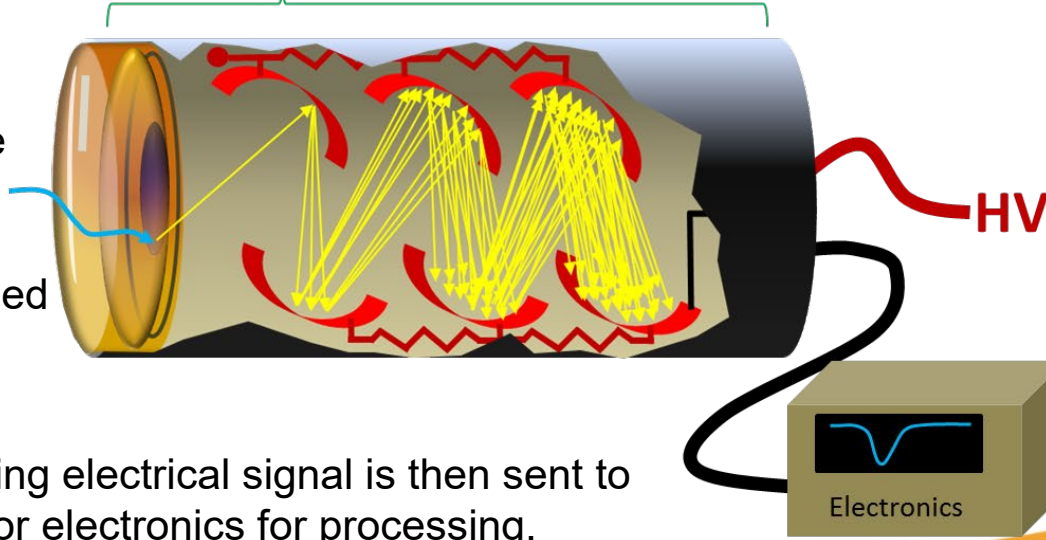


# Scintillation Detectors

$\gamma$  Ionizing radiation excites atoms in the scintillator. These atoms emit very faint light, which is amplified by a photomultiplier tube (PMT).



Light from the scintillator is converted to electrons by the PMT and amplified a million times or more through a succession of electrodes called 'dynodes'.



The resulting electrical signal is then sent to the detector electronics for processing.

# Commercial Scintillation-Based Detectors

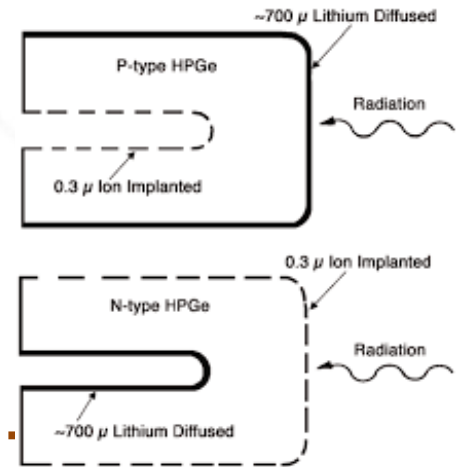
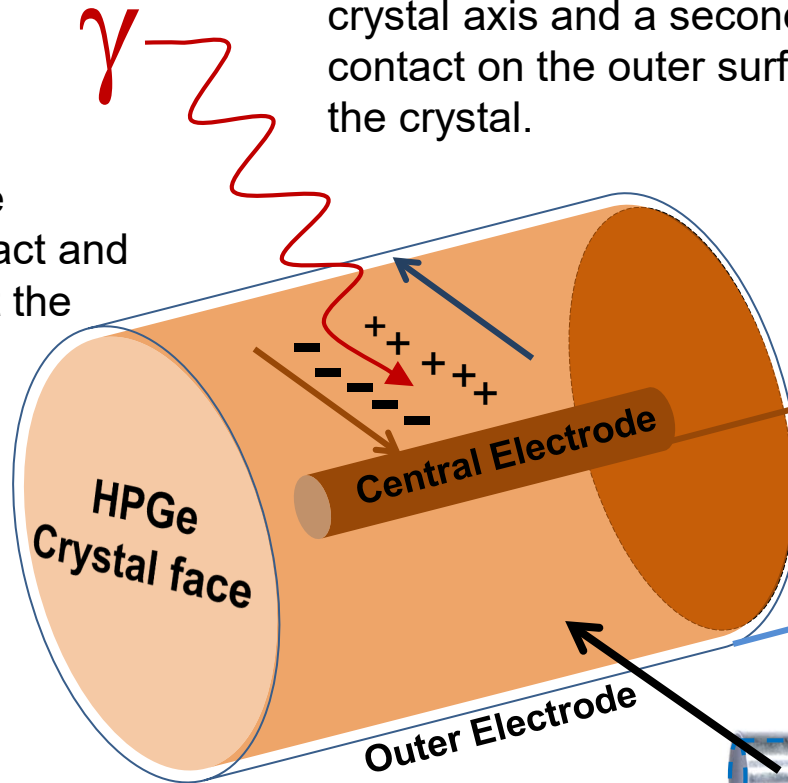


# High-Purity Germanium (HPGe)

Gamma rays create “electron – hole” pairs in the detector crystal.

When high-voltage is applied, electrons are collected at one contact and holes are collected at the other contact.

A coaxial HPGe detector has an electrical contact on the crystal axis and a second contact on the outer surface of the crystal.

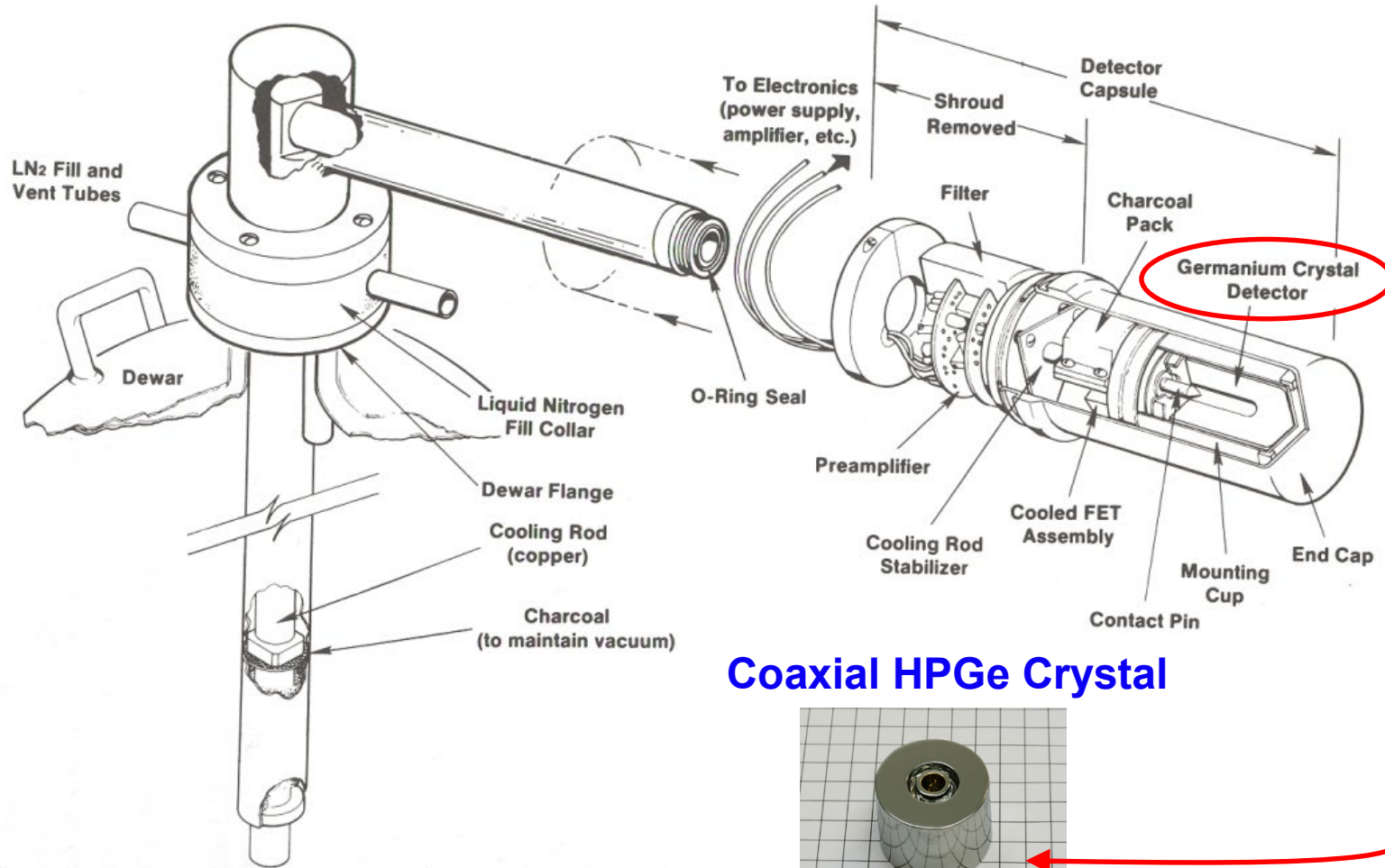


**HV & Signal**

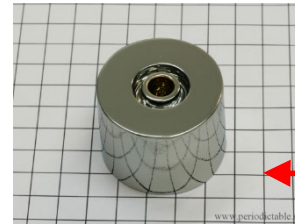


**HPGe detectors must be cooled to ~77 K (-321 F)**

# LN2-Cooled HPGe Schematic



Coaxial HPGe Crystal



# Commercial Semiconductor-Based Detectors





# Absolute and Intrinsic Efficiency

# Question Time!

- Which interaction is required to occur in our detector for us to do full-energy-peak gamma-ray spectroscopy?
  - a) Pair Production
  - b) Photoelectric Effect
  - c) Compton Scattering
  - d) Pair Annihilation

# Why Do We Care About Efficiency?

- Statistics for nuclide identification
- Estimation of detection distance
- Quantification of nuclide activity or mass
- Performing isotopic composition analysis
  - Uranium enrichment
  - Plutonium 'burn-up'
  - Isotopic ratios in general (e.g. Fukushima analysis)

# Quantifying Source Activity or Mass

$$Activity = \frac{C(E)}{Y(E)} \cdot \frac{1}{\varepsilon_{Abs}(E)}$$

$$Mass = Activity \cdot \frac{T_{1/2}}{\ln 2} \cdot \frac{A}{6.022E + 23}$$

$C(E)$ : count rate for a specific gamma-ray peak

$Y(E)$ : yield (branching ratio) for that gamma ray

$\varepsilon_{Abs}(E)$ : absolute detection efficiency at that gamma ray energy

$T_{1/2}$ : half life of the nuclide emitting that gamma ray

$A$ : atomic mass of this nuclide

# Detection Efficiency

- Absolute efficiency

$$\epsilon_{Abs} = \frac{\text{photons recorded}}{\text{photons emitted}}$$

- Intrinsic efficiency

Note: photons =  
full-energy photons

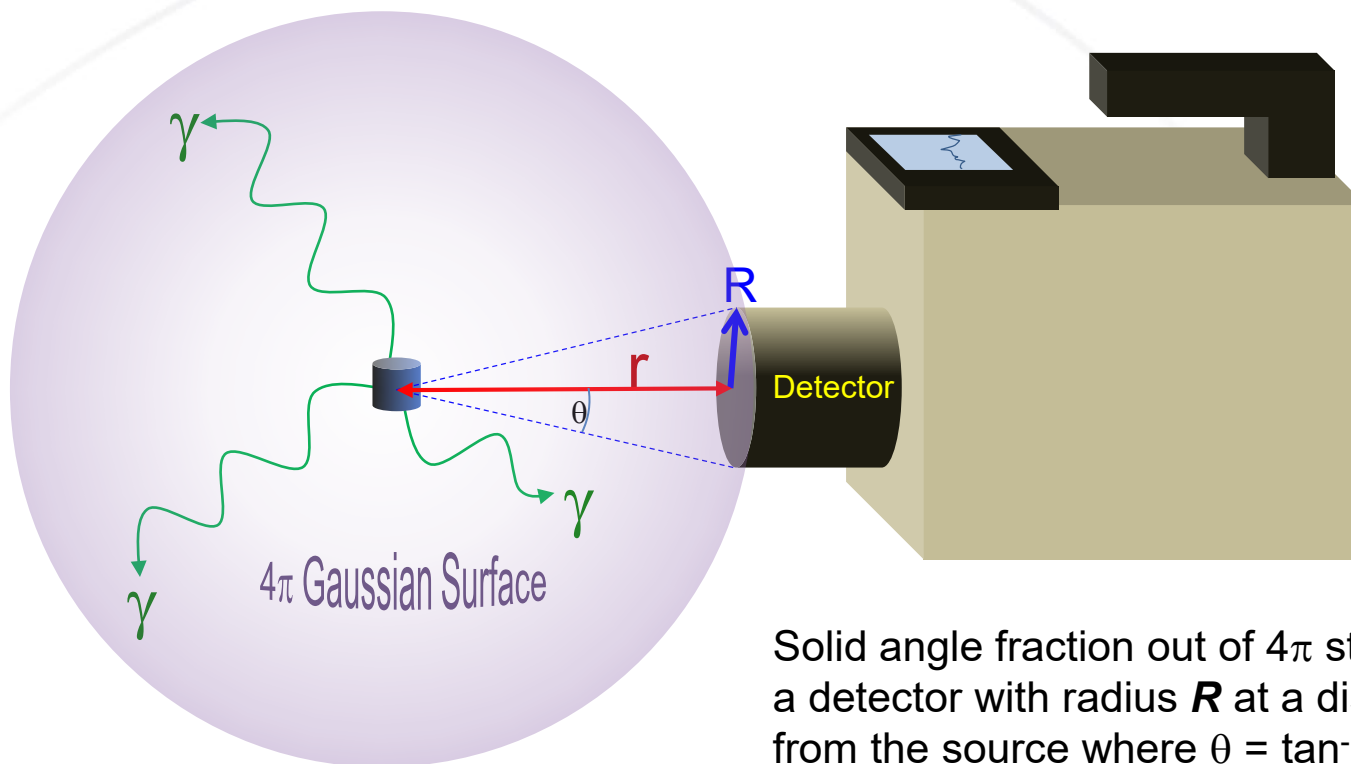
$$\epsilon_I = \frac{\text{photons recorded}}{\text{photons incident}}$$

- How are these related?

$$\epsilon_{Abs} = \epsilon_I \cdot \text{Atten} \cdot \frac{\Omega}{4\pi} \left. \vphantom{\frac{\Omega}{4\pi}} \right\} \text{Solid-Angle Fraction}$$

**Attenuation Factor**

# Detector Solid Angle Fraction

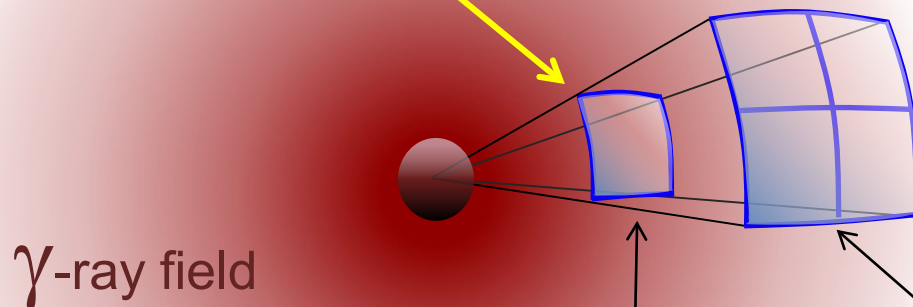


Solid angle fraction out of  $4\pi$  steradians for a detector with radius  $R$  at a distance  $r$  from the source where  $\theta = \tan^{-1}(R/r)$ :

$$\frac{\Omega}{4\pi} = \frac{1}{2}(1 - \cos \theta)$$

# The Inverse Square Law ( $1/r^2$ )

Let's say 1 square = the area covered by your detector.



$\gamma$ -ray field

distance =  $r$   
area =  $A$   
e.g. 400 cps



Count rate

$$C \propto \frac{1}{r^2}$$

Source-to-detector distance

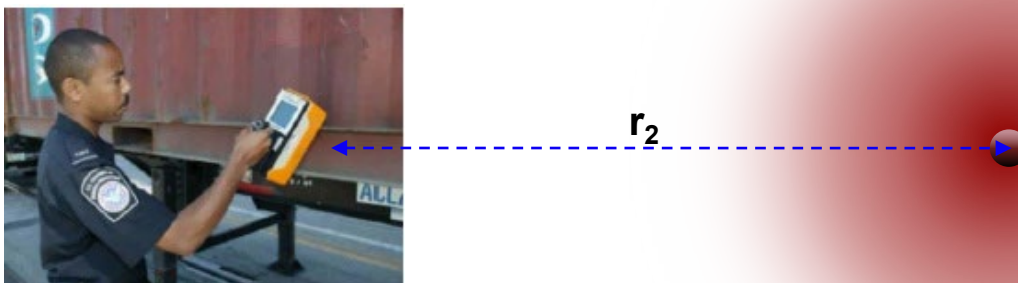
distance =  $2r$   
area needed for same rate =  $4A$   
Rate for 1 square = 100 cps

If you *double* the distance, the count rate drops by a factor of 4

# Why is distance important?

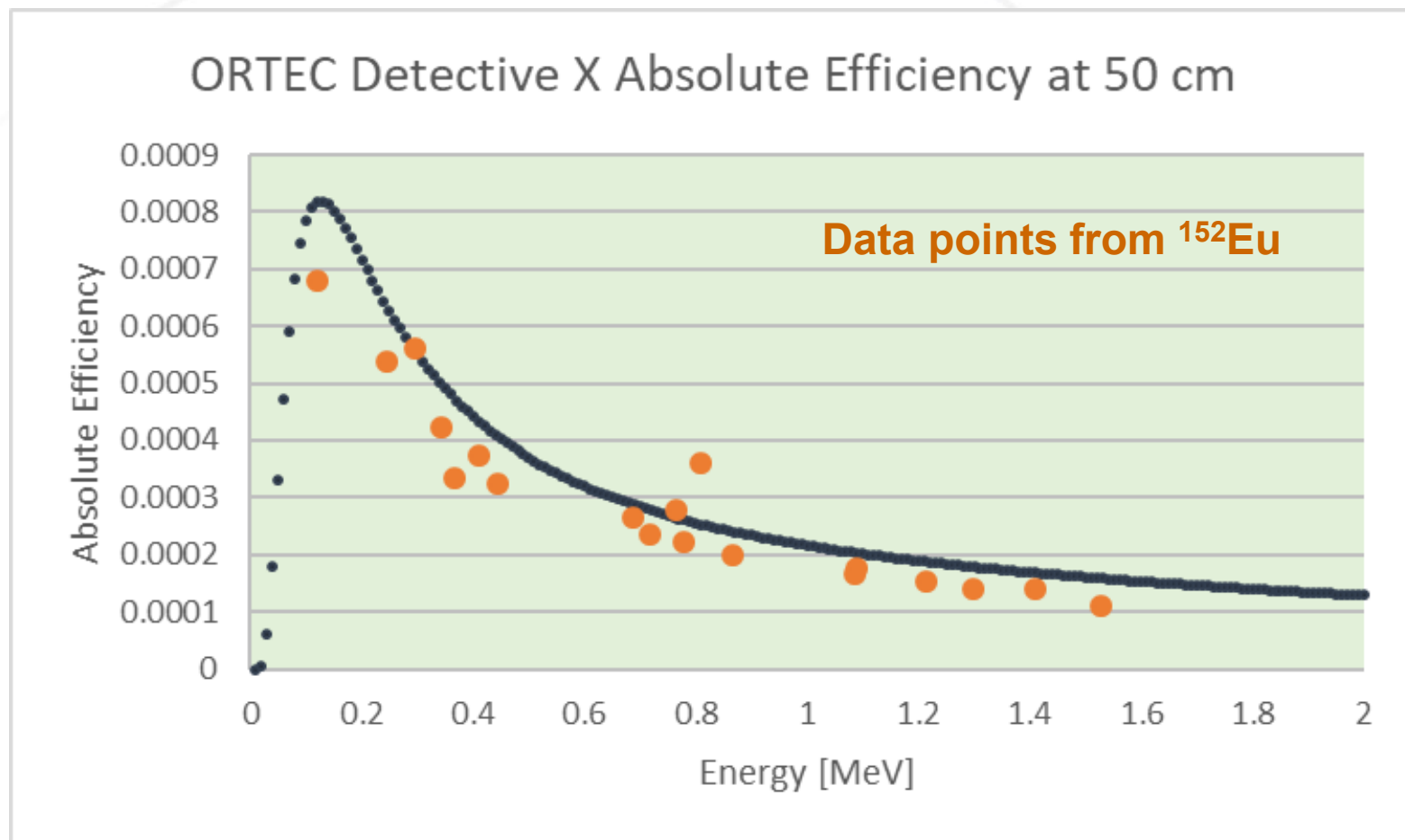
The observed dose rate in these two cases *could* be the same.

**We need to know the source-to-detector distance to calculate the activity or mass of the source.**



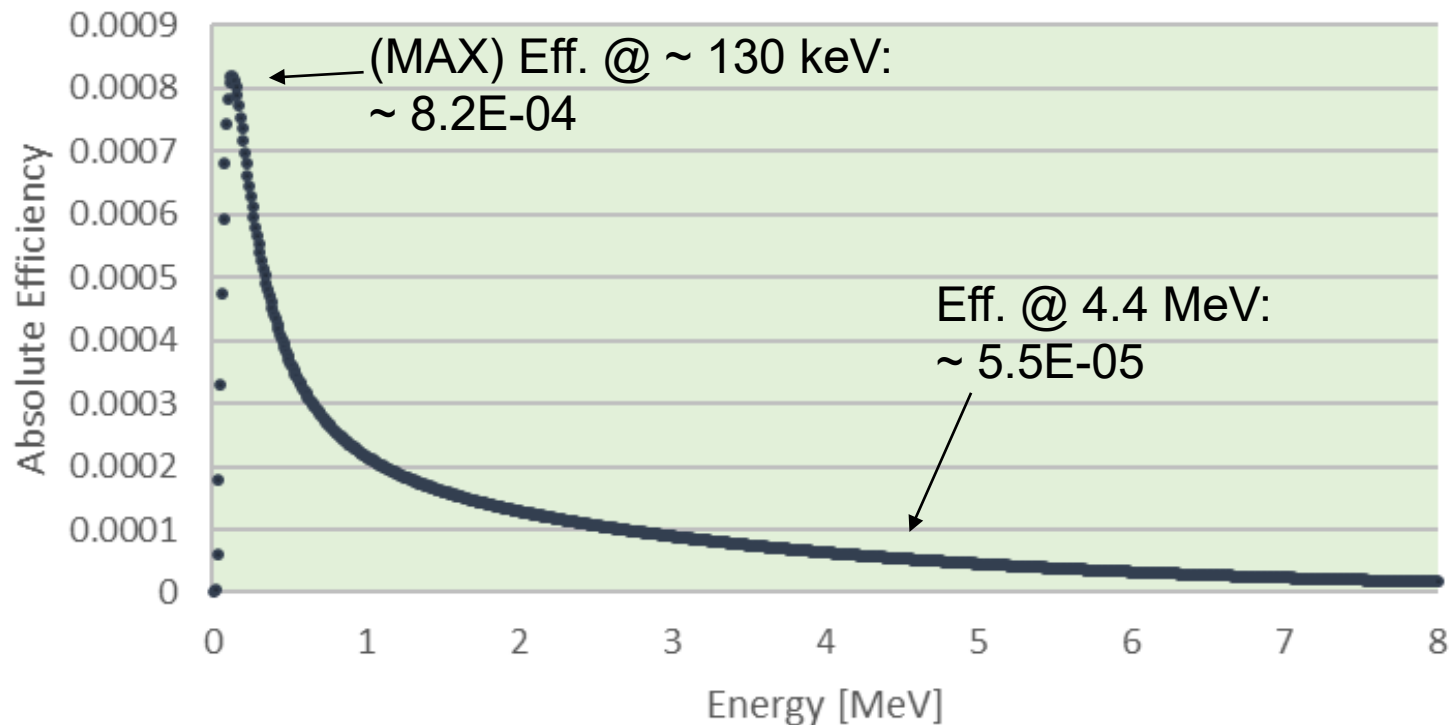
But the farther source is much more intense!

# Detective X Absolute Efficiency @ 50 cm



# Detective X Abs. Eff. @ 50cm to 8 MeV

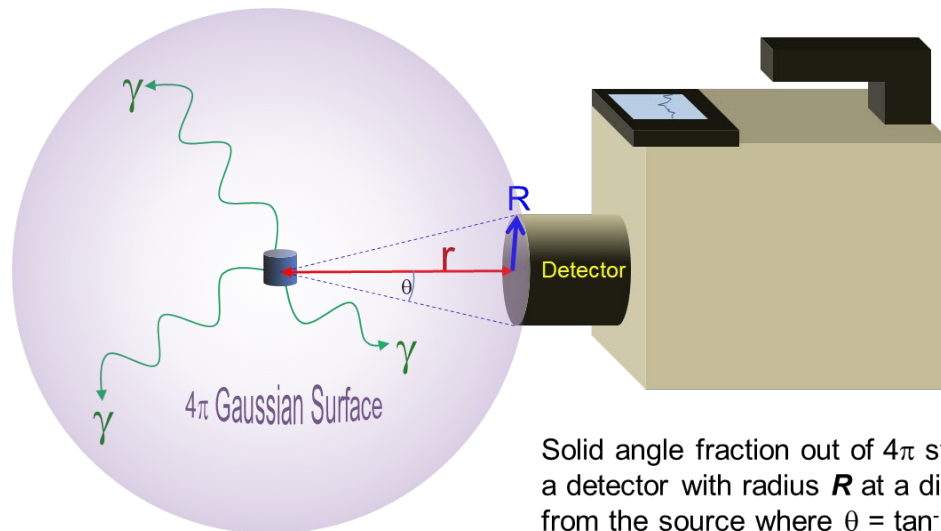
ORTEC Detective X Absolute Efficiency at 50 cm



# Question Time!

- What is the maximum solid angle fraction you could cover with a detector like an ORTEC Detective?

- a) 0.10
- b) 0.25
- c) 0.50
- d) 1.00

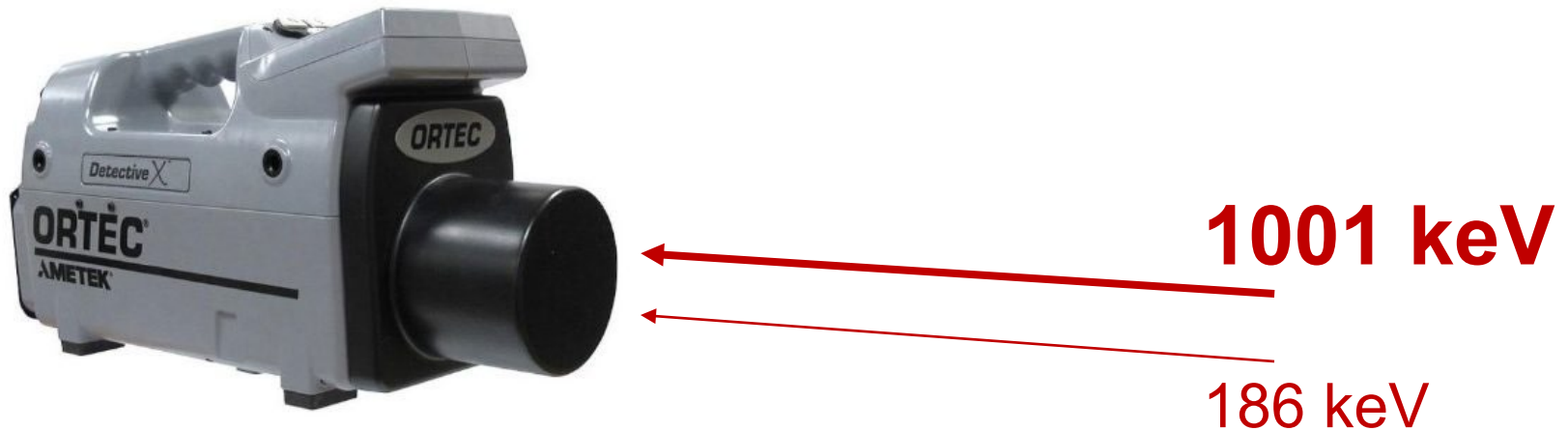


Solid angle fraction out of  $4\pi$  steradians for a detector with radius  $R$  at a distance  $r$  from the source where  $\theta = \tan^{-1}(R/r)$ :

$$\frac{\Omega}{4\pi} = \frac{1}{2}(1 - \cos \theta)$$

# Intrinsic Efficiency

Intrinsic detector efficiency quantifies the probability of full-energy detection of a photon of a particular energy that is incident on the face of the detector.

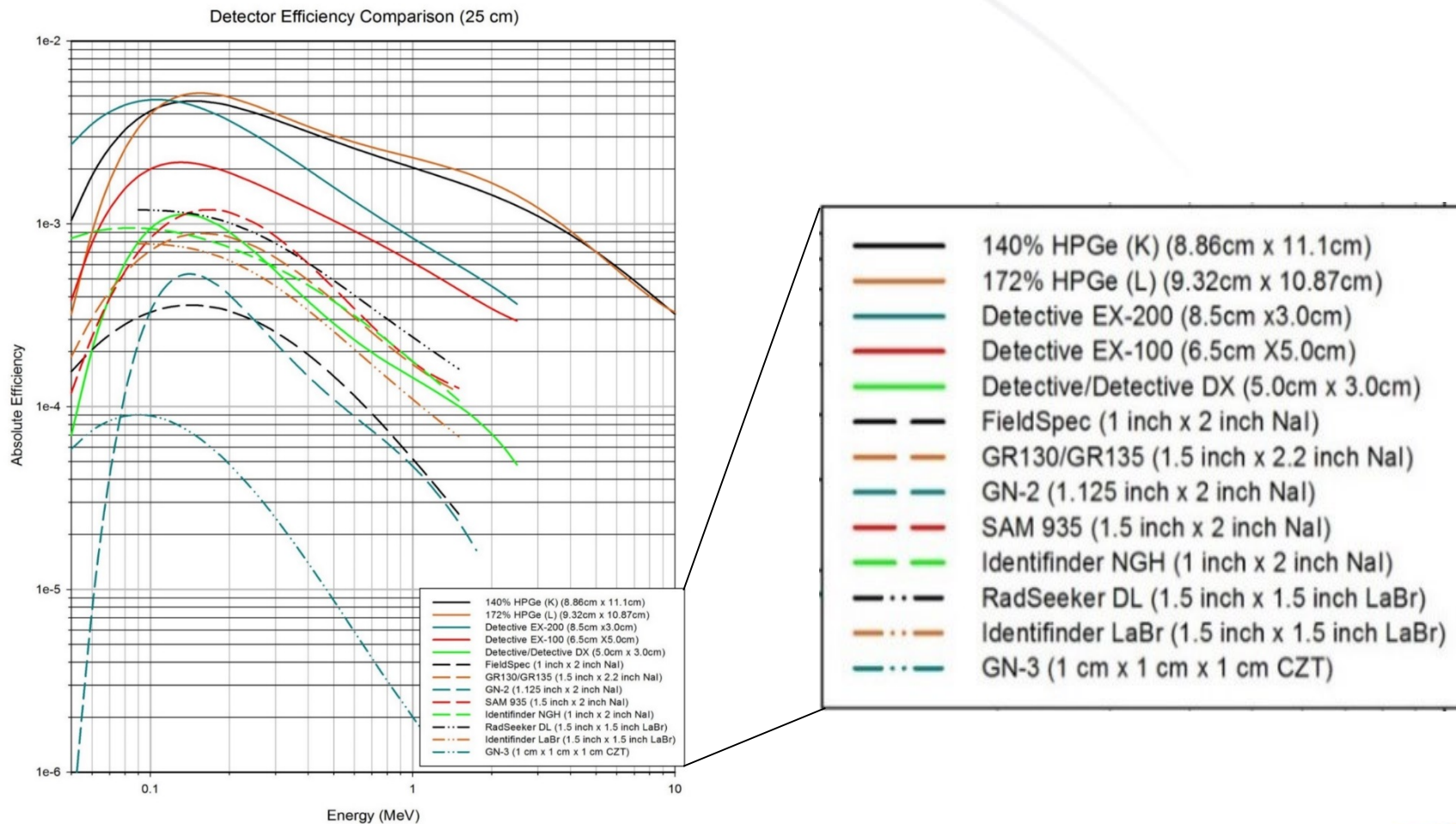


- a) assumes photons are incident on detector face
- b) full-energy detection → contributes to full-energy peak
- c) depends on incident photon energy

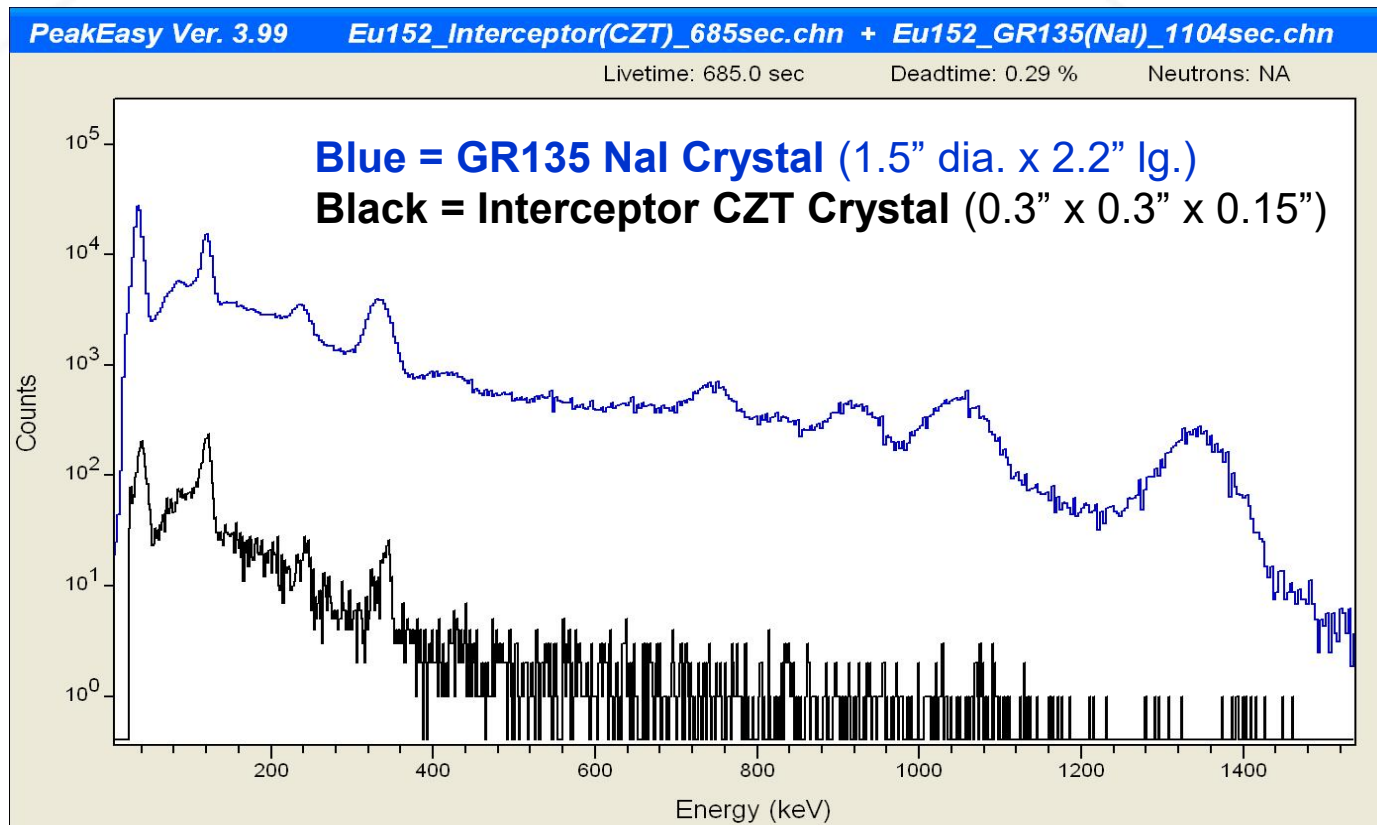
# Intrinsic Detector Efficiency

- Generally intrinsic detector efficiency is optimal at some low-intermediate energy ( $\sim 80\text{-}120\text{ keV}$ )
  - Below this energy gammas are more likely to be attenuated before entering the sensitive part of the detector.
  - Above this, gammas become more likely to Compton scatter in the detector as energy increases, and therefore not deposit their full energy.

# Example Intrinsic Efficiency Curves



# Importance of Intrinsic Efficiency

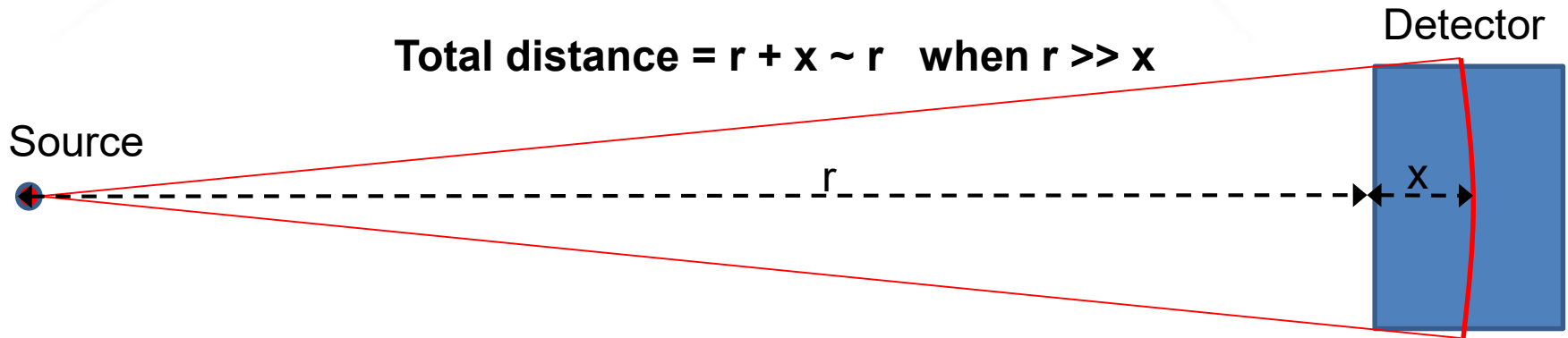


Both measurements of same Eu-152 source at 1 meter

# Average Interaction Depth

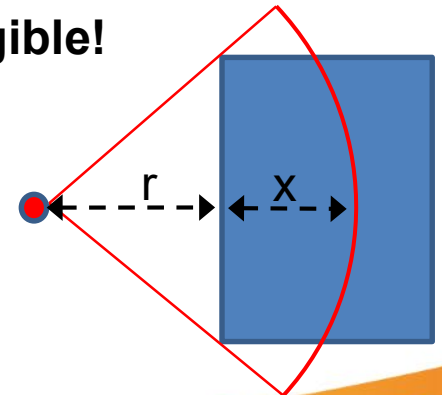
The average gamma interaction depth,  $x$ , in the detector depends on energy.

**Total distance =  $r + x \sim r$  when  $r \gg x$**

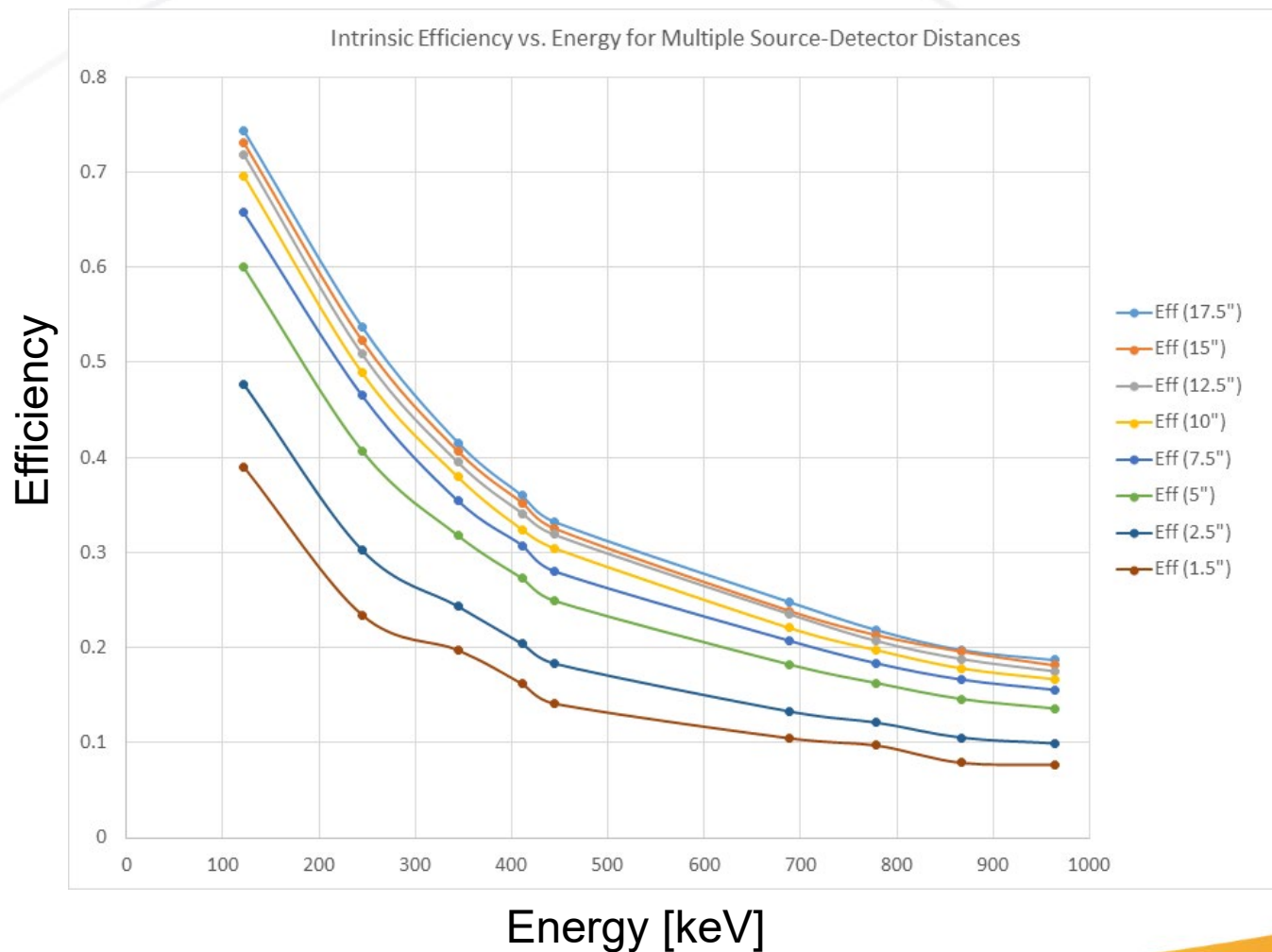


**But when  $r \cong x$ , the latter is not negligible!**

In this case, the distance that matters with regard to *solid angle*, as well as *intrinsic efficiency*, is that from the source to the average interaction depth inside the crystal



# Intrinsic Efficiency and Distance



# Relative Efficiency: Definition #1

- This definition concerns intrinsic detector efficiency coupled with the area of the detector face.
  - This is useful for comparing detectors.
- By convention, this is the **1332-keV** (Co-60) full-energy peak efficiency of any gamma detector relative to a 3" x 3" NaI **at 25 cm**
  - Usually, HPGe detectors are quoted as having a relative efficiency for comparison (e.g. 32%)

# Question Time!

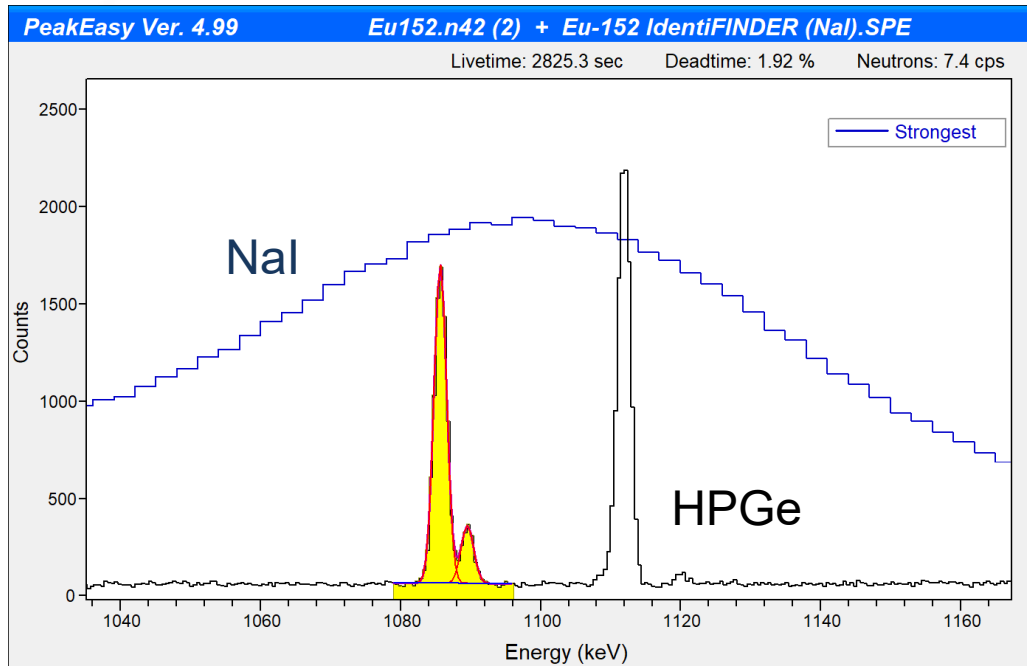
- A hand-held detector is placed at 10 feet and then at 20 feet from a strong point source. How would you best compare the intrinsic efficiency at each distance?
  - a) It is ten times higher at 10 feet
  - b) It is two times higher at 10 feet
  - c) It is essentially the same at 10 and 20 feet
  - d) It can not be determined from this information



# Resolution & Linearity

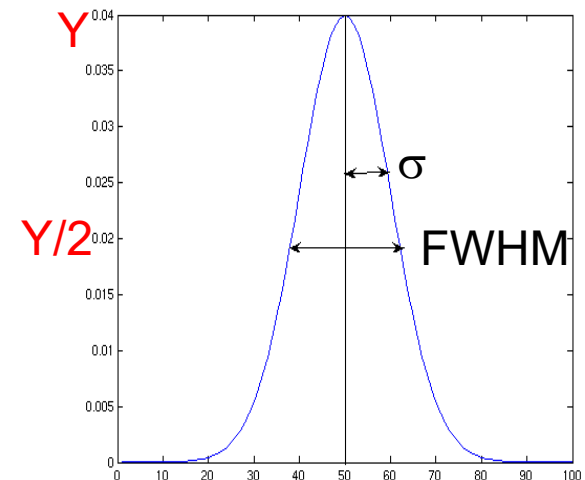
# What is Resolution?

Resolution is a measure of the width of spectral features such as full-energy peaks.



$$Y(x) = Y_{max}e^{-(x-x_0)^2/2\sigma^2}$$

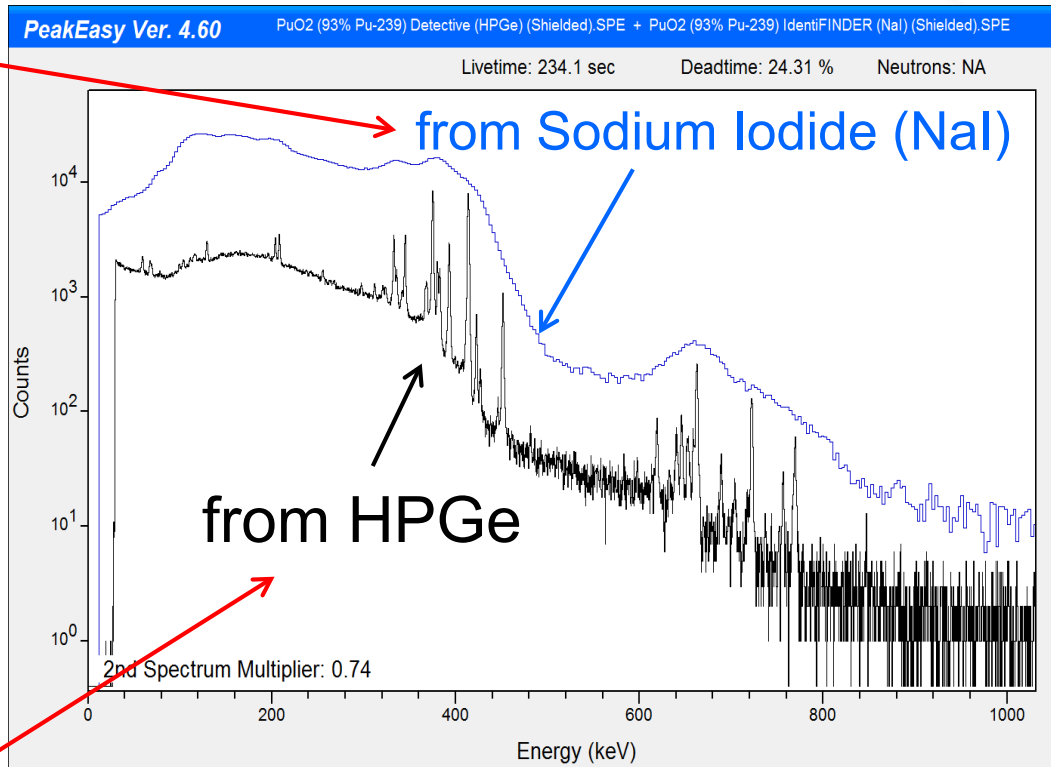
$$FWHM = 2.355\sigma$$



**FWHM = Full Width at Half Maximum**

# The Importance of Resolution

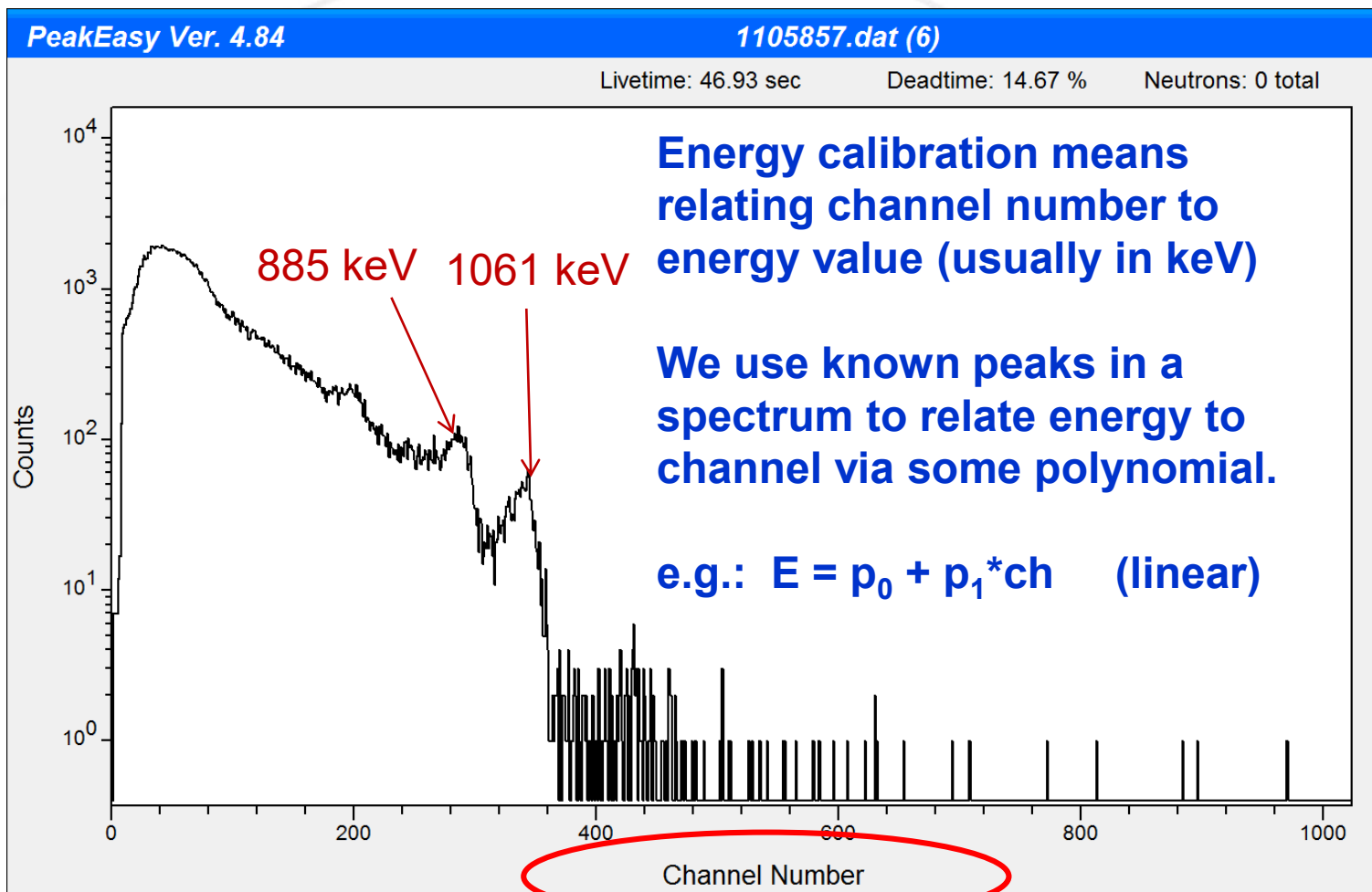
Two spectra of the same Pu item



HPGe is more of a burden but it provides data that are far more detailed and useful than low-resolution detectors (NaI, LaBr<sub>3</sub>)



# Energy Calibration



# Linearity

- A perfectly linear relationship between the size of pulses from the detector and the channel value (or energy) is highly desirable
- However, most detectors have non-linearities over the functional energy range in which they are used
  - As a group, scintillation detectors are notoriously non-linear, especially NaI.
  - HPGe and CZT are considerably more linear, but not perfectly so (especially at extended energy ranges)

# More on Linearity

- Many detectors are somewhat non-linear
  - In most cases, a linear calibration is not sufficient
  - 2nd order polynomial for a good detector, higher order polynomial for a poor detector
- Calibration spectrum must have at least as many peaks as the order of the polynomial being fit

# Question Time!

- Why is high resolution important? Choose the best answer(s)
  - a) We can better analyze peaks close in energy
  - b) It increases efficiency at higher energy
  - c) It allows us to cover a greater solid angle
  - d) It is more difficult to mask peaks

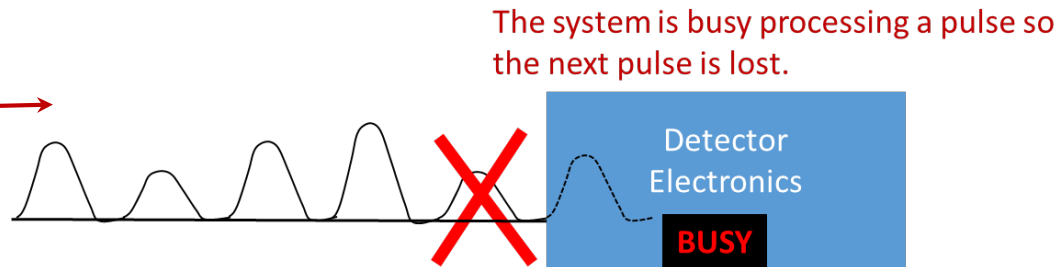
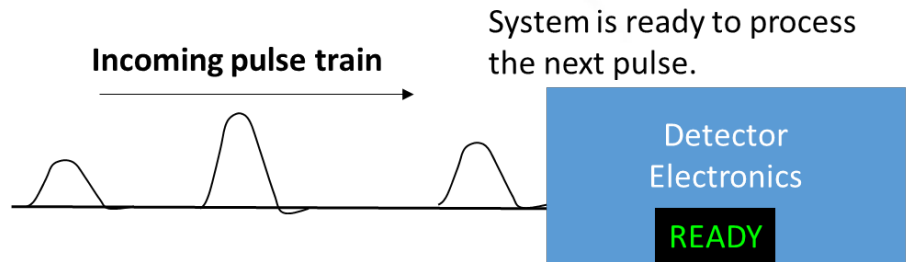
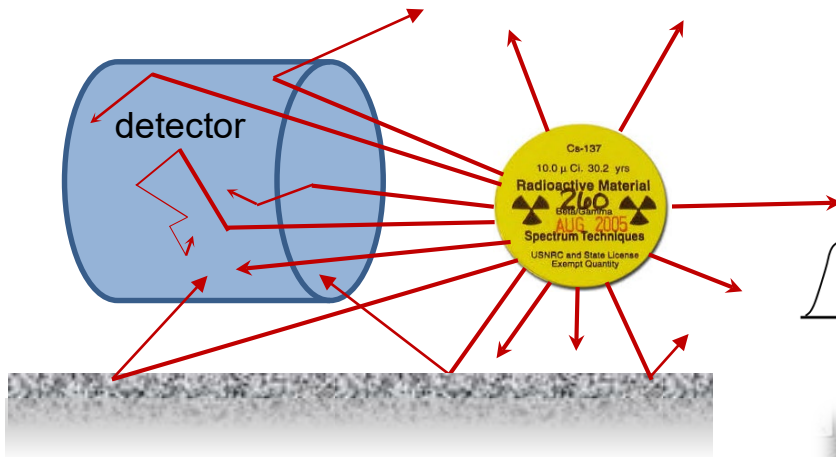


# Operational Issues & Limits

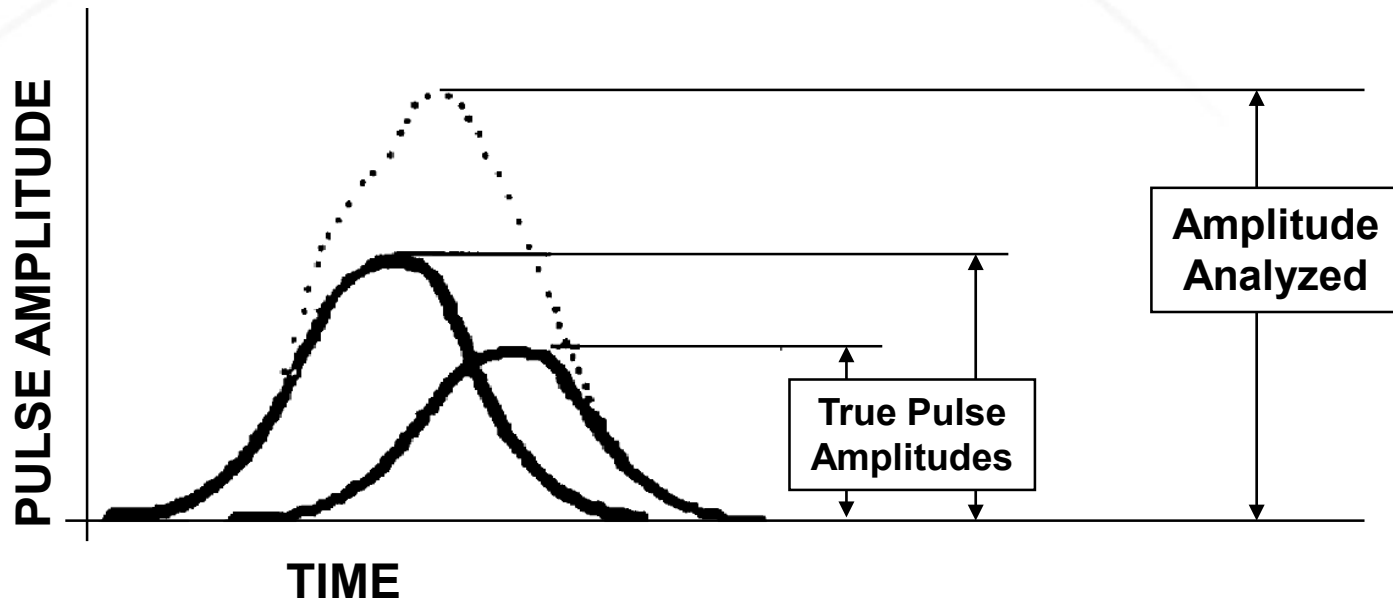
# Electronic Dead Time

Function of electronics where they are “dead” for a short time while processing a pulse.

Multiple gammas may hit the detector so close in time that the system can't process them all.

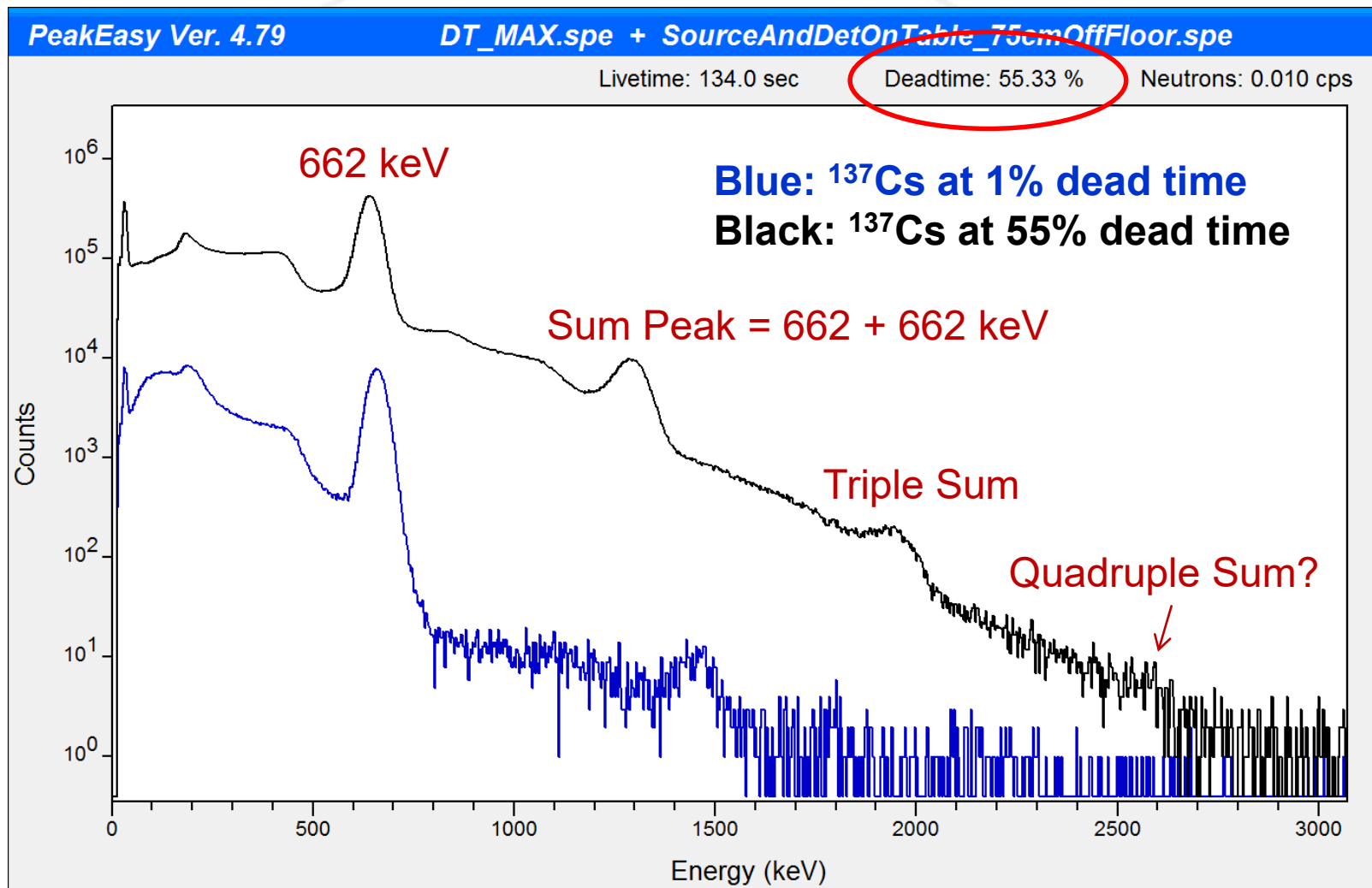


# Pulse Pile-up



Two or more  $\gamma$  rays are detected at almost the same time. The result is a combined pulse amplitude that is different from that of either pulse. Information on individual pulses is lost, and data, in the form of sum-peaks, are stored in the spectrum.

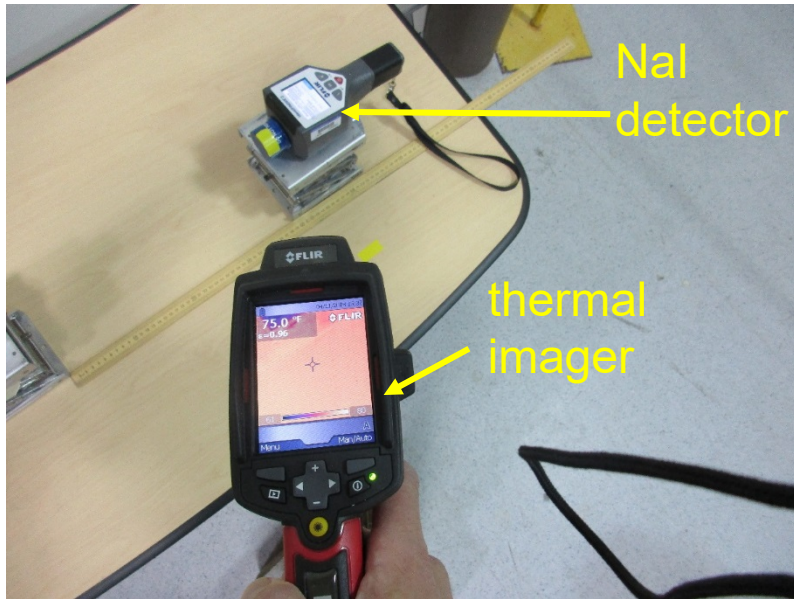
# Effects of High Count Rate



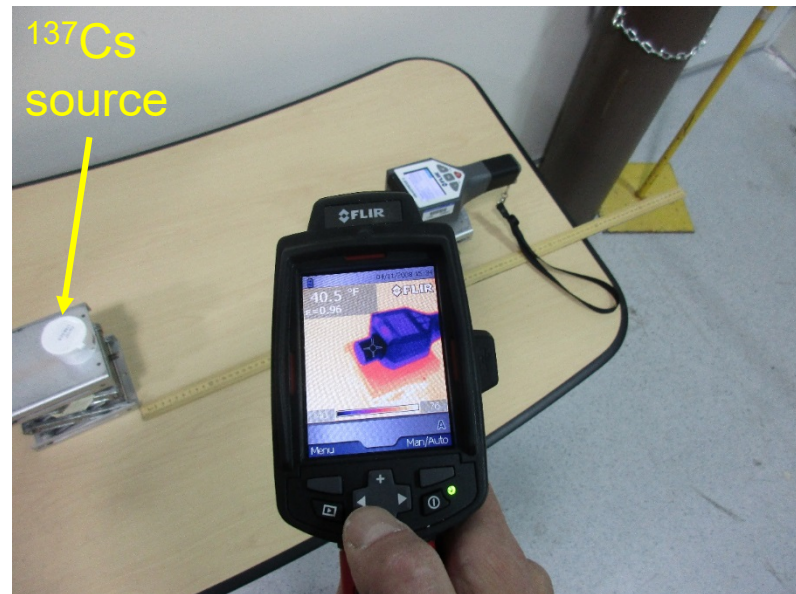
# Nal Temperature Dependence

A NaI detector was cooled in a refrigerator until it was 41 F and then data were taken with a  $^{137}\text{Cs}$  source as it warmed.

Room temp was approximately 75 F at table top.

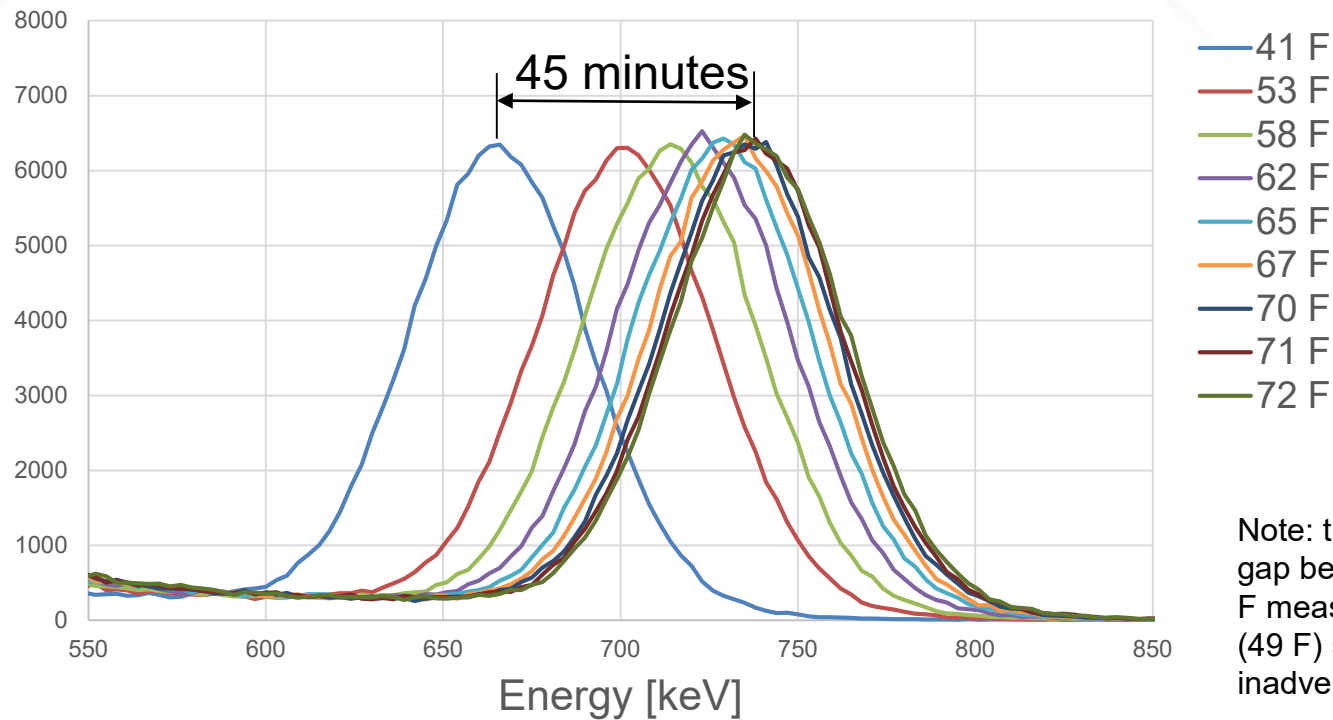


Initial detector temp was ~ 41 F at crystal.



Note: tape was placed on the detector and table top for a controlled emissivity.

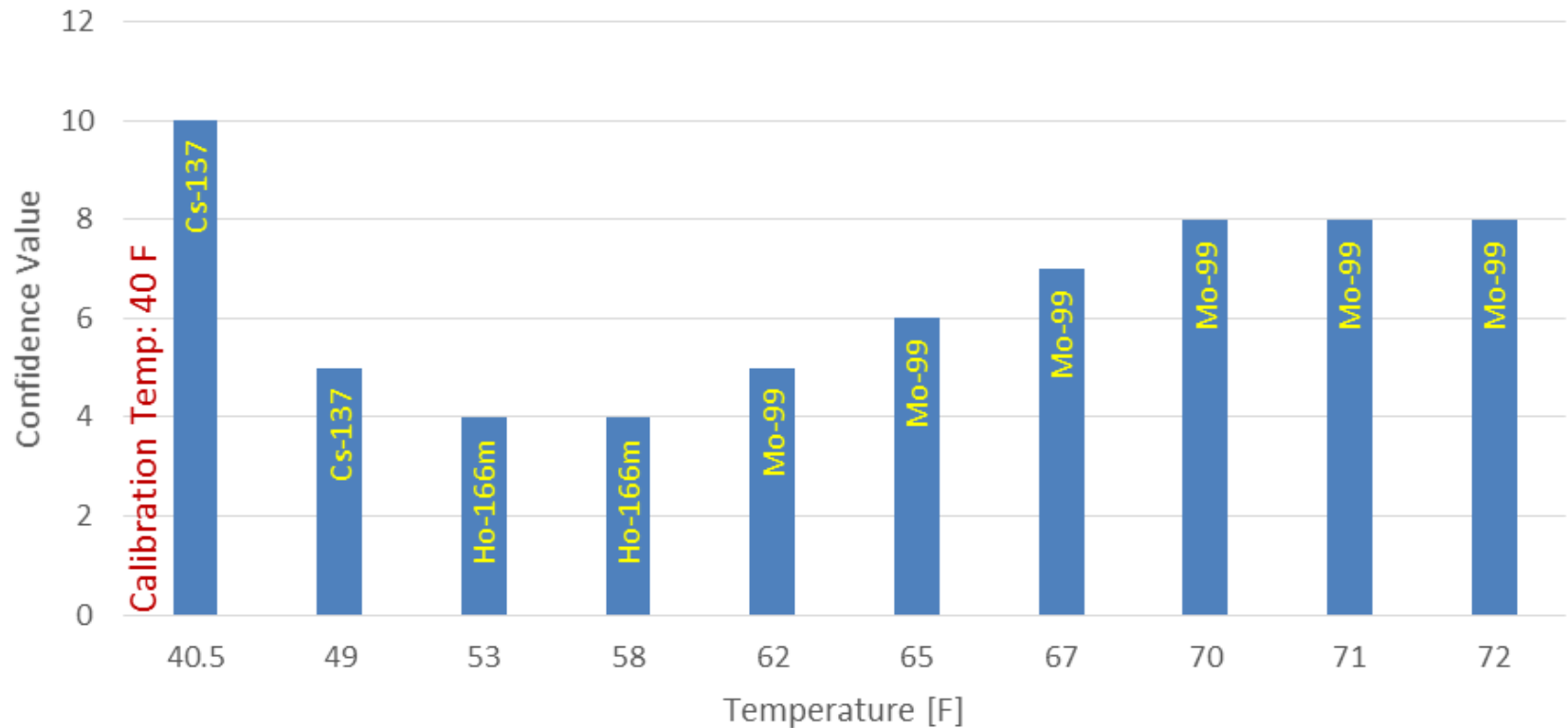
# $^{137}\text{Cs}$ 662-keV Peak versus Temperature



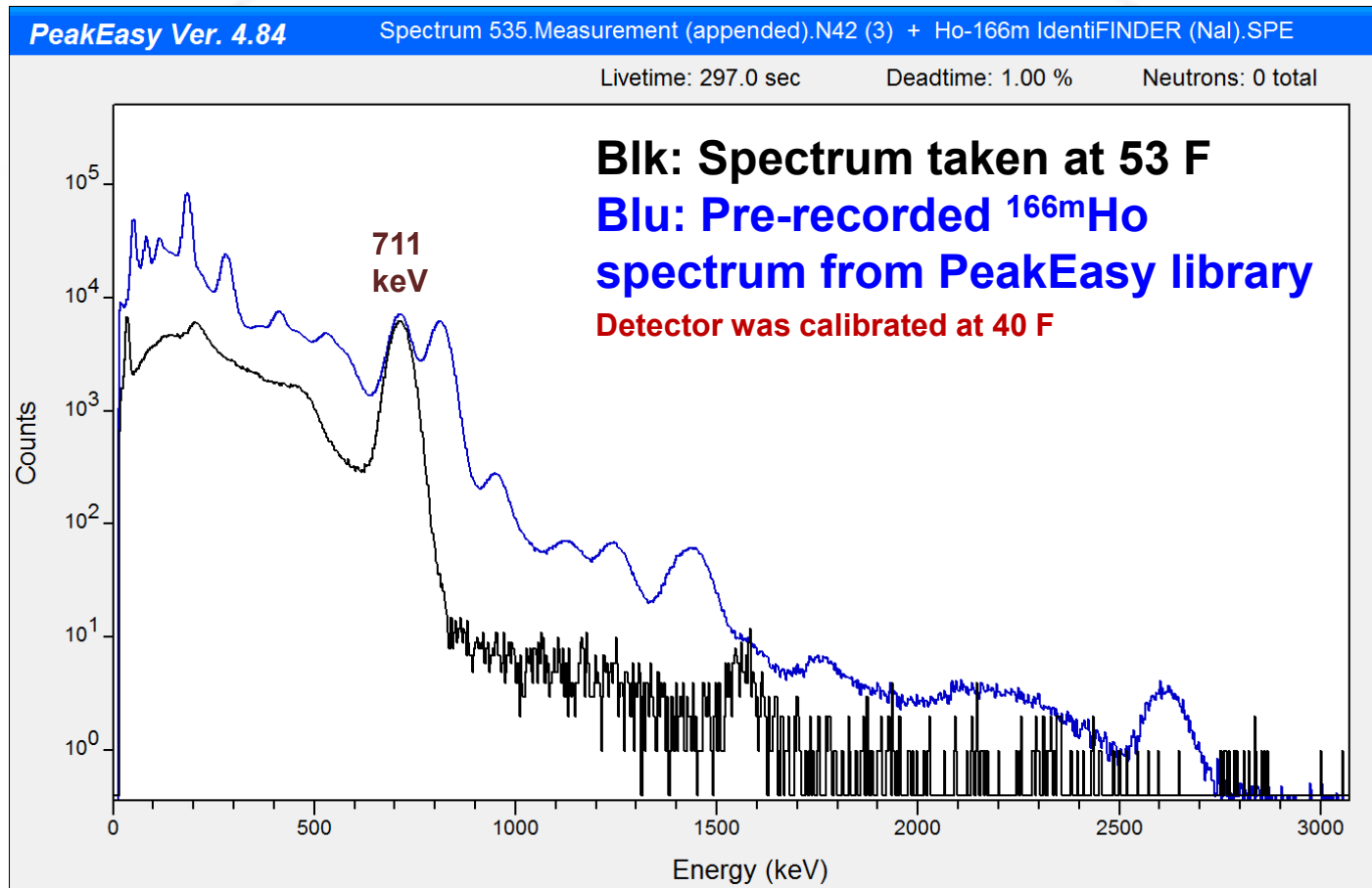
Note: there was a 10-minute gap between the 41 F and 53 F measurements as the 2<sup>nd</sup> (49 F) spectrum was inadvertently not saved.

# Nuclide ID results vs. Temperature

Nuclide ID vs Temperature



# Why $^{166m}\text{Ho}$ for the 53° F spectrum?



# Scintillation Detector Scorecard

- Low resolution (-)
  - Few information carriers result in poor statistics
  - Generation of signal is inefficient, typically requiring  $\sim 100$  eV/carrier
- Temperature sensitivity (-)
  - Gain fluctuations and non-linearities result in difficult energy calibrations
- Efficiency (+)
  - Large NaI and PVT detectors can be made with exceptional total efficiency
- Cost (+)
  - These are generally less expensive than semi-conductors

# HPGe Detector Scorecard

- Best energy resolution of gamma detectors (+)
  - Due to excellent charge carrier mobilities
- Large crystal growth allows good efficiency (+)
  - 140-160% not uncommon (relative to a 3" x 3" NaI)
- Must cool to LN temperatures to avoid thermal excitation of electrons (-)
- Most expensive of gamma detector types (-)
- Field units can be cumbersome to handle (-)

# CdZnTe (CZT) Scorecard

- Room-temperature operation
- Typically can attain 3% resolution but with new signal processing now  $\sim 1\%$
- Very poor efficiency
  - Difficult to grow large crystals ( $\sim 6 \text{ cm}^3$  max)
- Poor hole mobility requires very sophisticated electrodes and read out



# Question Time!

- Which is the best detector?
  - a) HPGe as it has the best resolution
  - b) NaI as it does not require cooling
  - c) Plastic scintillator as it is can be made to cover a very large area
  - d) CZT as its poor efficiency is useful in high-rad environments



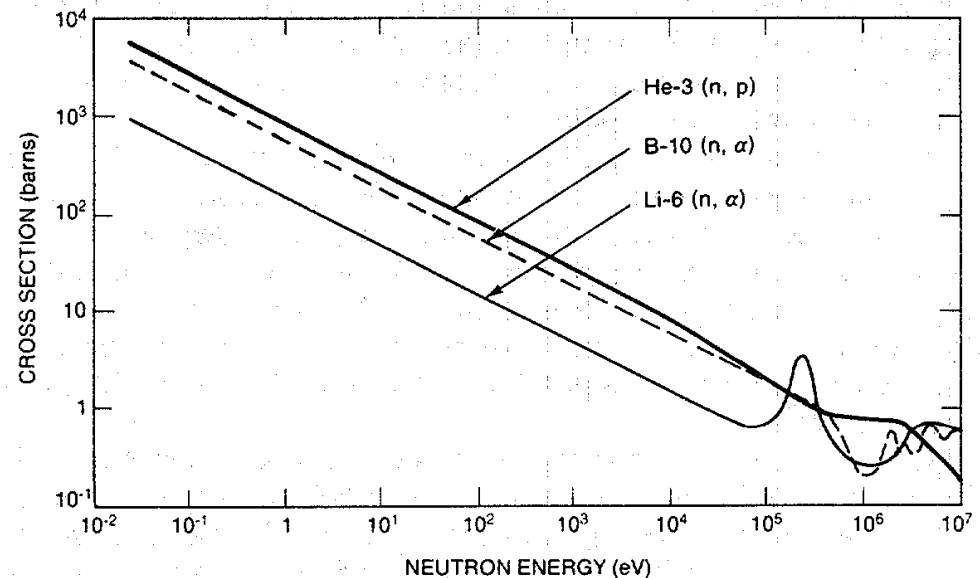
# Neutron Detection

# Mechanisms for Neutron Detection

- None are direct since they are neutral particles
  - Must detect charged secondary particles or gamma rays
- Two primary detection modalities
  - Neutron capture reactions release protons, alphas, recoil atoms, gammas, or fission fragments that can subsequently be detected
  - Scatter neutron off light nucleus (H or He) transferring some energy to it, which then ionizes surrounding material

# Neutron Cross Section for Common Materials

- Cross section is strongly a function of neutron energy ( $1/v$ )
  - Most commercial detectors are moderated
- Many materials have resonances in cross section superimposed on  $1/v$  relation
  - Example:  $^6\text{Li}$

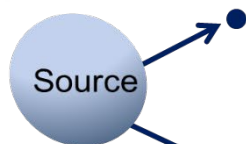


*Passive Nondestructive Assay of Nuclear Materials (1991)*

# Neutron-Sensitive Gas Detectors

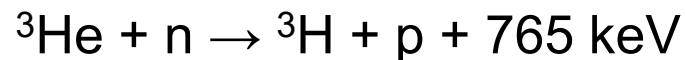
- $^3\text{He}$ 
  - Typically operated  $< 10$  atm (except RIIDs)
  - $\sim 75\%$  efficient for thermal neutrons
  - Currently, the most common neutron detector in portal monitors
- $^{10}\text{BF}_3$ 
  - Typically operated  $< 1.5$  atm (recombination occurs at high pressures)
  - $< 50\%$  efficient to thermal neutrons
- $^{10}\text{B}$ -lined tubes (“Straws”)
  - Neutron interaction occurs on walls, resulting in secondary charge within gas ( $< 10\%$  efficient for thermal neutrons)

# $^3\text{He}$ Neutron Detector

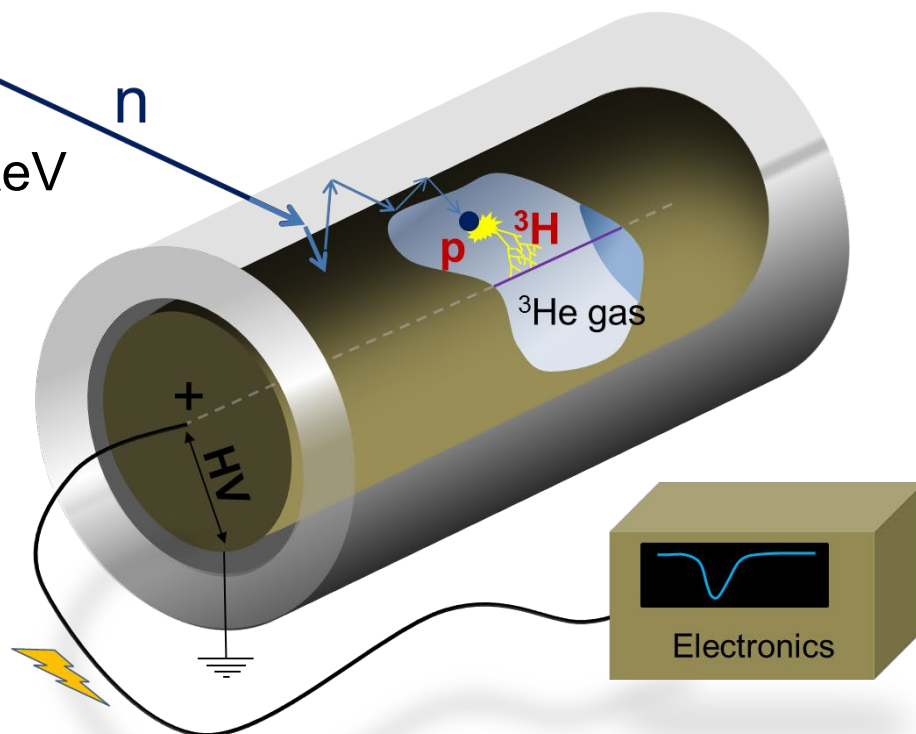


Neutrons are moderated (thermalized) by **polyethylene** surrounding  $^3\text{He}$  tube.

n

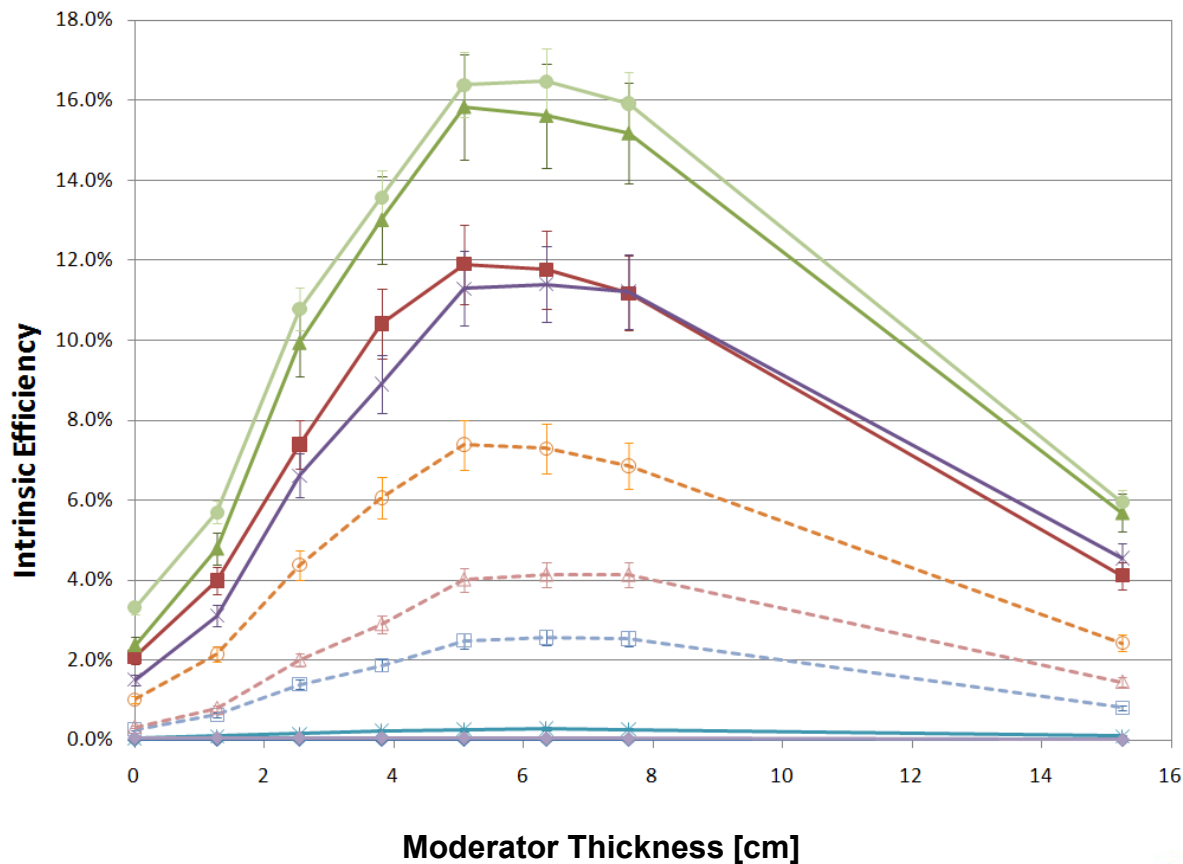


These thermal neutrons are captured by  $^3\text{He}$  nuclei and produce tritium ( $^3\text{H}$ ) and protons (**p**), which in turn ionize the gas. The resulting electrons and ions are then collected at the central wire and tube wall.



The resulting electrical signal is then sent to the detector electronics for processing.

# Moderation Effects on Detector Response



# Neutron-Sensitive Scintillators

- Plastic or liquid organics
  - Used more for fast neutron detection
  - Very sensitive to gamma rays
  - Efficiency can be  $\sim {}^3\text{He}$
- ${}^6\text{Li}$ -loaded glass
  - Used in older GR-135s handheld detectors (new model uses He-3 tube)

# Next Generation Neutron Detectors

- CLYC ( $\text{Cs}_2\text{LiYCl}_6:\text{Ce}$ ) gamma-neutron scintillation crystal
- $^6\text{LiFZnS}(\text{Ag})$  scintillator screens with wavelength shifting fibers
- $^6\text{Li}$  foils with  $^4\text{He}$  gas (cheap and abundant)
- And a host of others

# Problems with Neutron Detection

- Useful spectroscopy can be difficult since neutrons rarely deposit their full energy in the detector
  - For  $^3\text{He}$  detectors, neutrons must be thermalized for detection therefore forfeiting all incident energy information.
- RIID detectors will only tell you the neutron count rate
- Can be sensitive to gamma rays as well, so setting a proper threshold is important (pulse shape discrimination might also be necessary)
- Cosmic ray spallation in nearby massive and dense materials will cause false neutron counts (e.g. cargo of car batteries)

# Question Time!

- Cadmium (Cd) is a thermal neutron absorber. Which configuration will give you the highest count rate in your bare He-3 detector?
  - a) Bare  $^{252}\text{Cf}$ , Cd, 0.5-inch of Water, detector
  - b) Bare  $^{252}\text{Cf}$ , 0.5-inch of Water, Cd, detector
  - c) Bare  $^{252}\text{Cf}$ , Cd, detector
  - d) Cd, 0.5-inch of Water, detector



# Basic Statistical Concepts

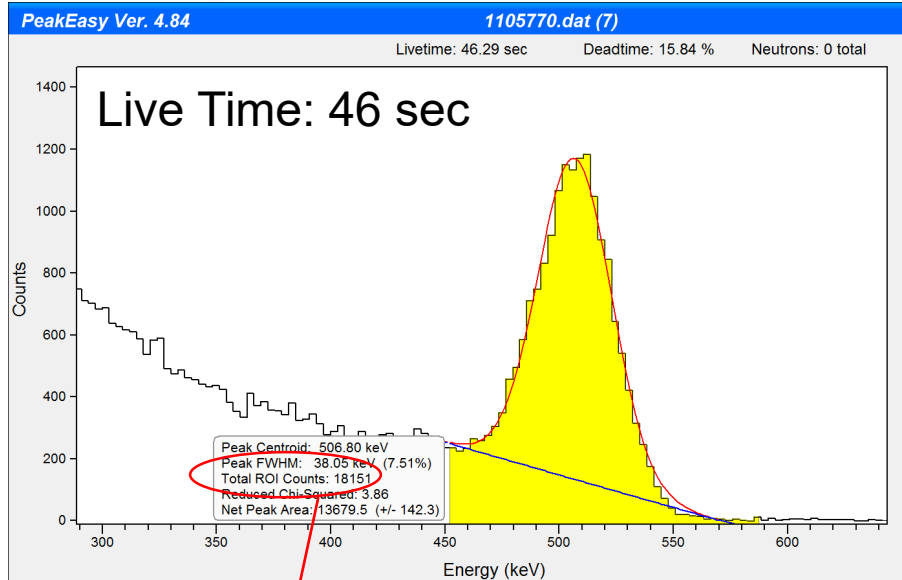
# Statistics

- For a measured number of *gross* counts, **N**, from a random nuclear decay process, the standard deviation is:  $\sigma = \sqrt{N}$
- Relative Standard Deviation:  $\sigma_R = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$
- What is the % uncertainty (or RSD) if  $N = 100$ ?
- How many counts do we need to get 1% error?

The terminology 'standard deviation', 'uncertainty', and 'error' are often interchanged.

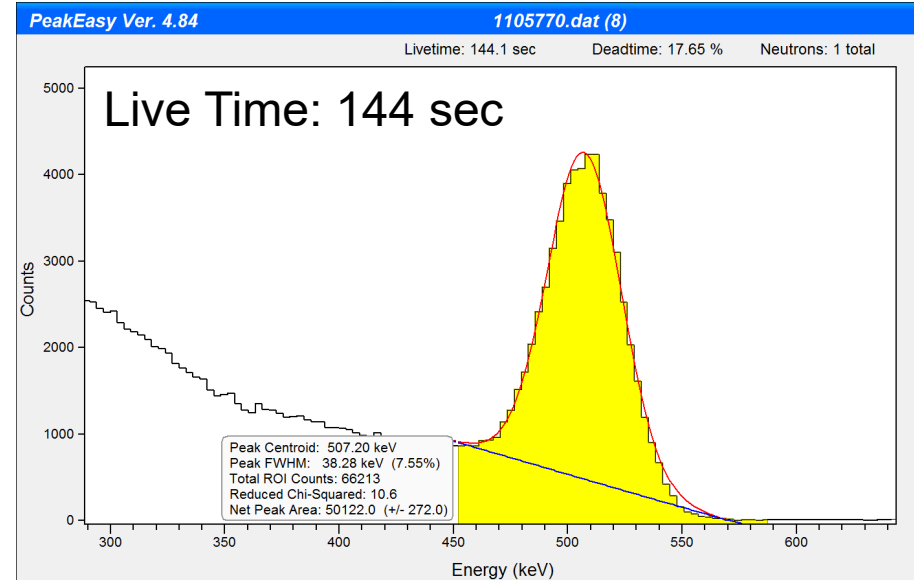
# Uncertainty on Gross Counts

If you count three times as long, your uncertainty drops by a factor of  $\sqrt{3}$ .



$$N = 18151$$

$$\sigma_R = \frac{\sqrt{18151}}{18151} \rightarrow 0.7\%$$



$$N = 66213$$

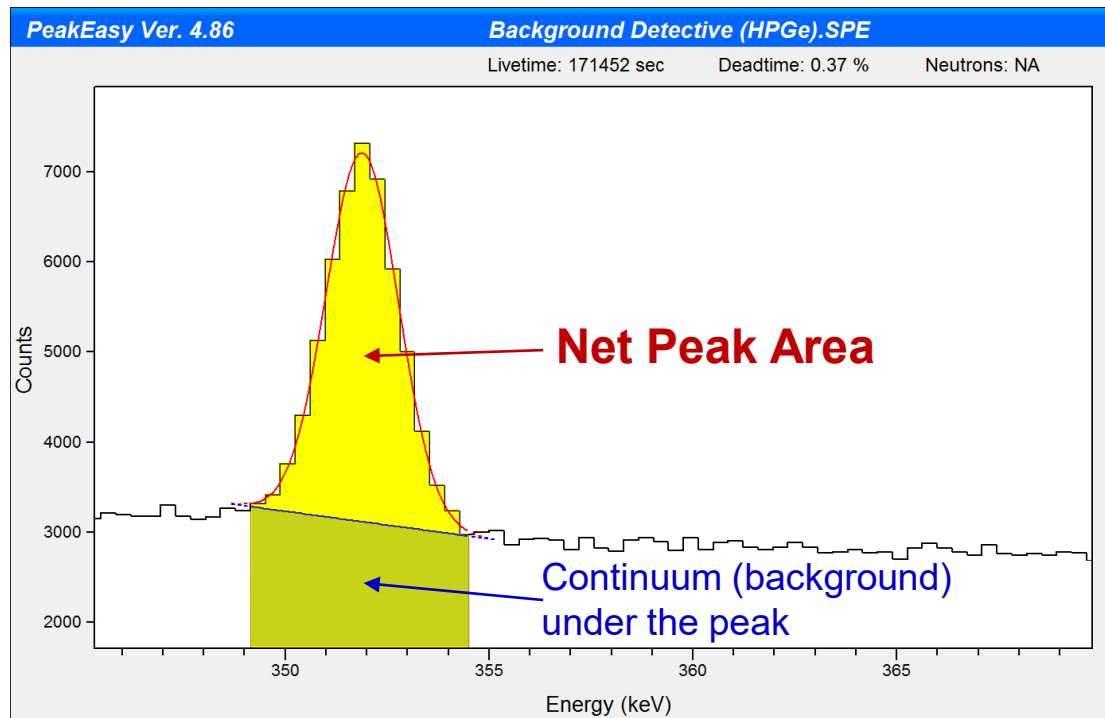
$$\sigma_R = \frac{\sqrt{66213}}{66213} \rightarrow 0.4\%$$

# Uncertainty on Net Counts

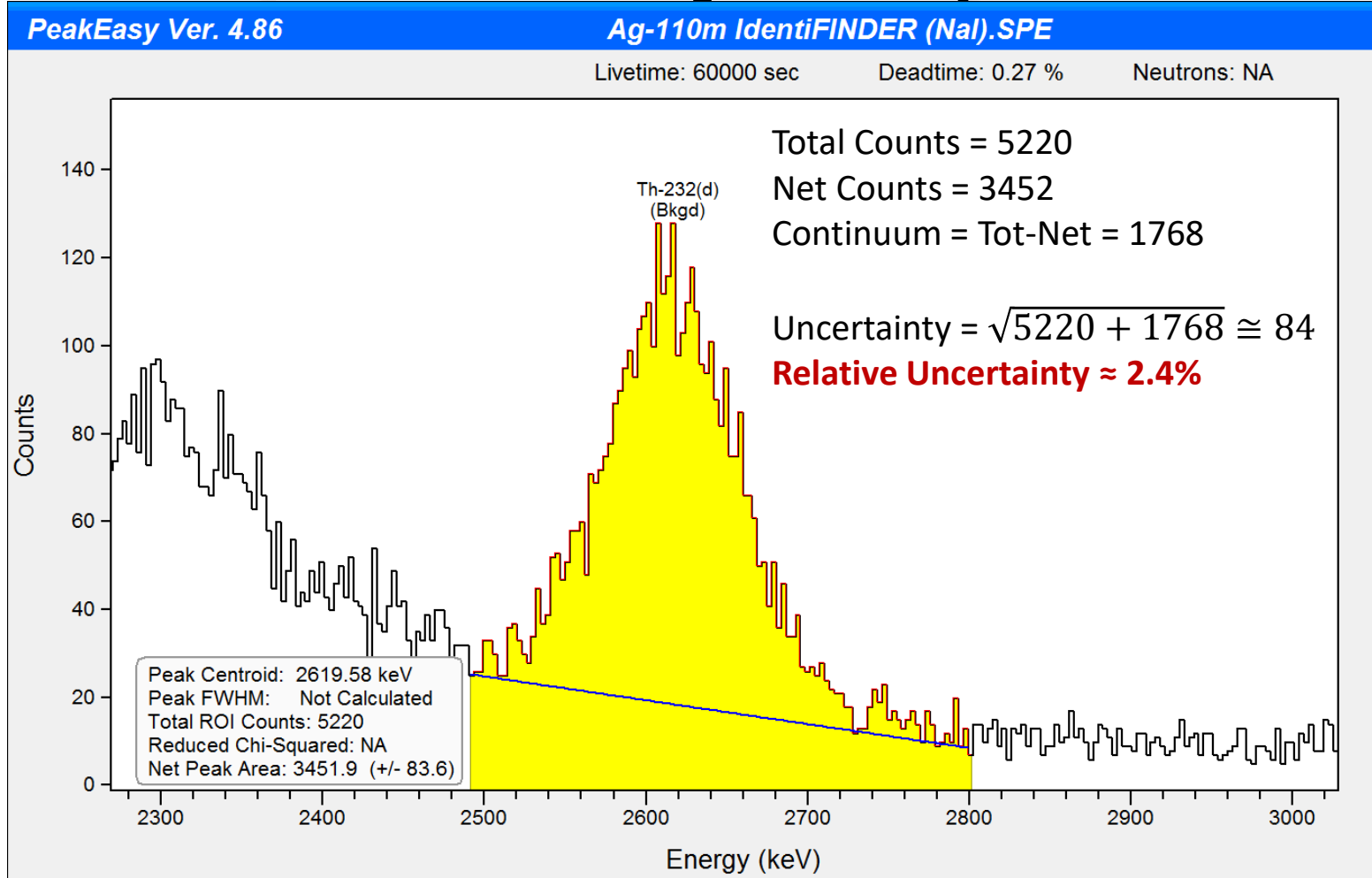
We are usually interested in the NET peak area.

Net Area = Total Counts - Continuum

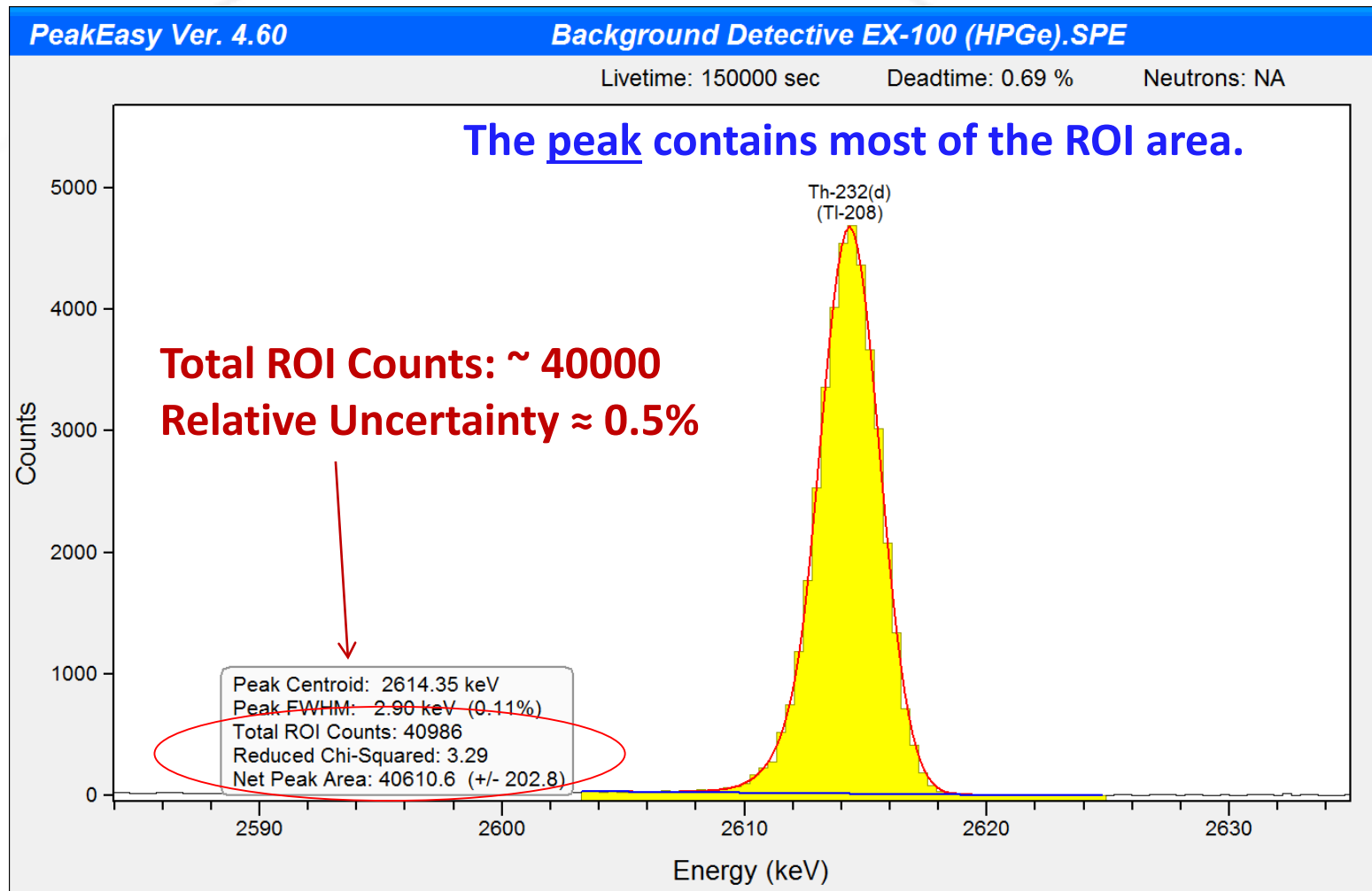
$$\text{Uncertainty} = \sqrt{\text{Total} + \text{Continuum}}$$



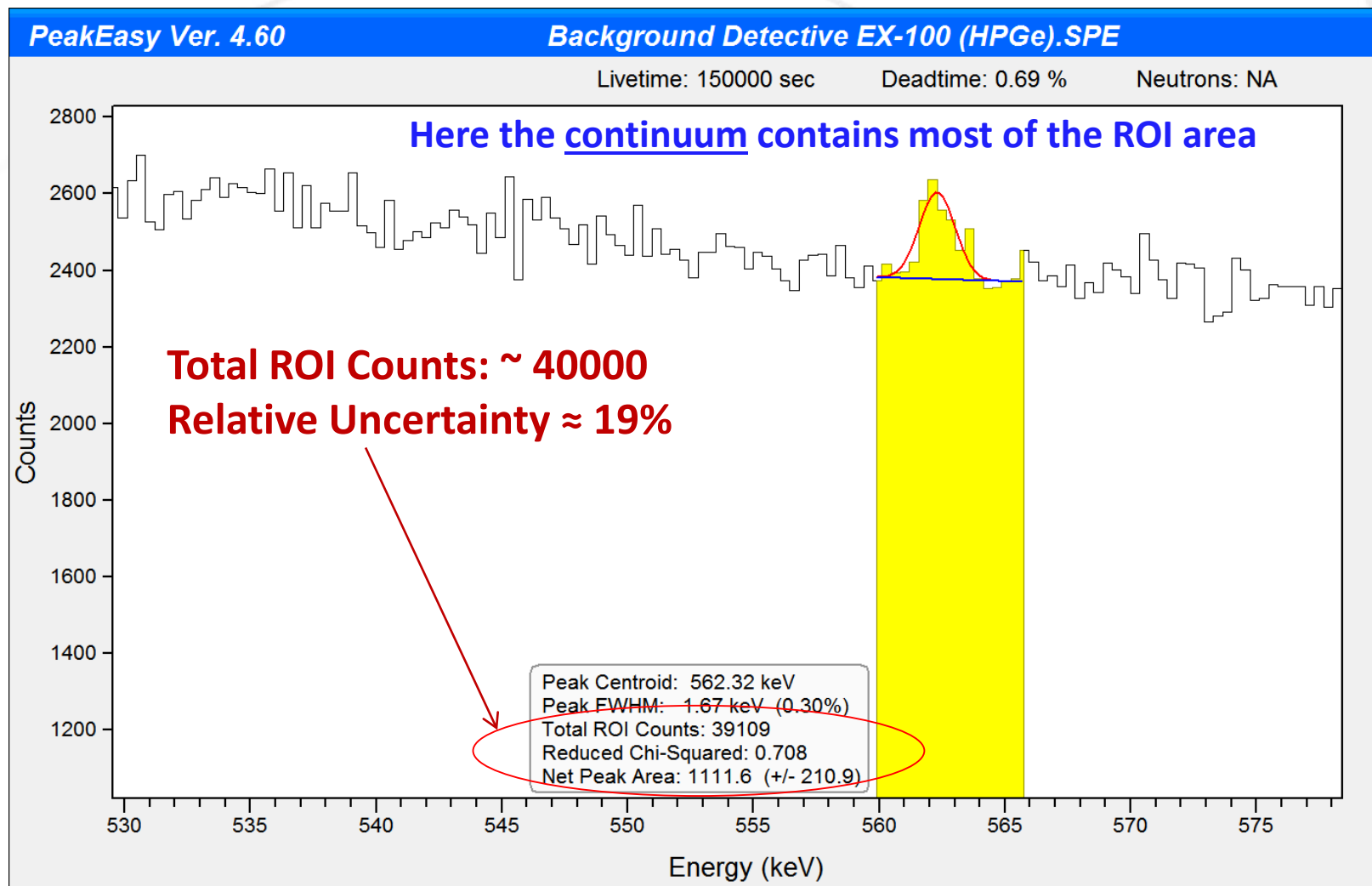
# Net Area Uncertainty Example



# Large Peak on Small Continuum



# Small Peak on Large Continuum



# Question Time!

- Folks often say a small peak can get ‘washed out’ by an intense continuum from higher-energy photons. What does the continuum really do?
  - a) It attenuates the peak
  - b) It increases the relative uncertainty on the peak area
  - c) It decreases the relative uncertainty on the peak area
  - d) It reduces the energy but not the intensity of the peak

# Summary

- General knowledge of detector concepts is important for spectroscopic analysis
- Although the general concepts are important to master, there is often a lot of variation from one detector to the next. Sometimes even with identical models from the same company.
- It is very helpful to be familiar with the idiosyncrasies of the most common detectors from which you receive or collect data.